
U.S. NUCLEAR WASTE TECHNICAL
REVIEW BOARD

REPORT TO
THE U.S. CONGRESS
AND
THE SECRETARY OF ENERGY



January to December 1996



UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD

1100 Wilson Boulevard, Suite 910
Arlington, VA 22209

March 1997

The Honorable Newt Gingrich
Speaker of the House
United States House of Representatives
Washington, D.C. 20515

The Honorable Strom Thurmond
President Pro Tempore
United States Senate
Washington, D.C. 20510

The Honorable Federico Peña
Secretary
U.S. Department of Energy
Washington, D.C. 20585

Dear Speaker Gingrich, Senator Thurmond, and Secretary Peña:

The Nuclear Waste Technical Review Board (Board) herewith submits its *Report to the U.S. Congress and the Secretary of Energy – 1996 Findings and Recommendations* in accordance with the requirements of the Nuclear Waste Policy Amendments Act of 1987, Public Law 100-203.

Congress created the Board to evaluate the technical and scientific validity of the Department of Energy's program to manage the permanent disposal of the nation's civilian spent fuel and high-level radioactive waste. Specifically, the Board is charged with evaluating the DOE's site-characterization activities at Yucca Mountain, Nevada, as well as activities relating to the design of the repository and to the packaging and transport of spent fuel and high-level radioactive waste. In its report, the Board summarizes the major findings, conclusions, and recommendations that have resulted from Board activities during calendar year 1996. We believe that the information contained in this report will be useful to policy makers and Department of Energy managers and staff as they consider during the coming months the status and future of the civilian radioactive waste management program.

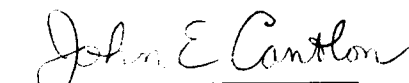
This year saw much progress in the exploration program at Yucca Mountain, with the exploratory studies facility nearing completion. Testing and evaluation within the facility continues, and new data are being gathered at an increasing rate. In light of this progress, the Board finds that there are three major areas of concern, which are discussed in this report. The first is the need for an east-west tunnel across the potential repository block, at repository depth, as a primary method of reducing uncertainties related to hydrogeologic issues. The second is the

distinction which must be made between the Department of Energy's viability assessment (VA), scheduled to be announced in 1998, and a technically defensible decision on the site's suitability to be a repository, which will be implied in the Secretary of Energy's report to the President in 2000. The third involves the issues surrounding repository design, as impacted by waste package design, thermal loading, and a changing hydrogeologic environment, among other things. These three issues are discussed at length in this report, as well as other scientific and technical matters of concern to the Board.

In early 1997, eight new members were appointed to the Board and a new chairman was appointed by President Clinton. The Board welcomes Drs. Daniel B. Bullen, Florie A. Caporuscio, Norman L. Christensen, Jr., Paul P. Craig, Debra S. Knopman, Priscilla P. Nelson, Richard R. Parizek, and Alberto A. Sagüés, and welcomes to the chair Dr. Jared L. Cohon, a member of the Board since June 1995. At the same time, the following members will leave the Board for other pursuits: Drs. John E. Cantlon (former chairman), Clarence R. Allen, Garry D. Brewer, Edward J. Cording, Donald Langmuir, and John J. McKetta, Jr. The Board also would like to acknowledge the contributions to this report by Drs. Patrick A. Domenico and Ellis D. Verink, Jr., whose appointments expired in April 1994, but who continued to serve as consultants until the recent appointment of replacements.

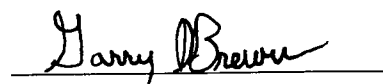
We thank you for the opportunity to serve the nation and the Congress. As the new members continue the work of the Board, we hope they will assist you in furthering the goal of safe and cost-effective management of civilian spent nuclear fuel and defense high-level waste.


Sincerely,

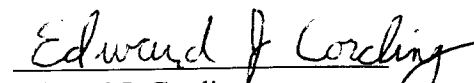

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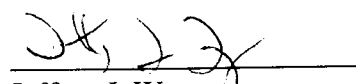

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Executive Summary

The Department of Energy's (DOE) *Program Plan* (DOE 1996a) officially introduced a new program milestone, the viability assessment (VA). The VA is to be completed by September 30, 1998. According to the DOE (DOE 1996d), the viability assessment will include four components: "(1) the preliminary design concept for the critical elements for the repository and waste package; (2) a total system performance assessment, based upon the design concept and the scientific data and analysis available by September 30, 1998, describing the probable behavior of the repository in the Yucca Mountain geological setting relative to the overall system performance standards; (3) a plan and cost estimate for the remaining work required to complete a license application; and (4) an estimate of the costs to construct and operate the repository in accordance with the design concept."

Perhaps the single most important technical decision facing this program is determining the suitability of Yucca Mountain as a site for a repository. The Board believes that the VA will not provide adequate information for that decision. Rather, it is an assessment that the site continues to be a candidate that requires additional study, leading to a determination whether it is suitable to be recommended to the President for repository development in 2001. Nothing has been found to date to indicate that the site is unsuitable.

The DOE believes that additional studies beyond those planned for the VA will be needed to evaluate the site's suitability, and the Board agrees. In particular, more information is needed on the geologic, hydrologic, and geochemical properties of the repository-level rock to confirm that a repository of useful size can be sited there. A major concern is the magnitude and distribution of the water flow, particularly in the proposed emplacement area which is to the west of the existing main tunnel. A small tunnel extended across this area is needed to observe water flow, as well as the rock structure, in this unexplored region. The Board concludes that such exploration and observation should be completed prior to the site suitability evaluation.

Another important issue to be assessed prior to completing the site-suitability evaluation is the thermal effect of the emplaced waste on water and vapor flow. Significant information will be gained from the tunnel-scale thermal tests, which the DOE has begun.

The Board believes that a VA can serve an important function in focusing and integrating the program and, when needed, adjusting its course. However, the Board also realizes that the planned VA may trigger other significant decisions such as selecting the location of a centralized facility for storing spent fuel. The VA may be used in ways that attach more significance and substance to it than may be warranted.

About four years would elapse between selection of a site for a centralized storage facility and the first receipt of commercial spent fuel there. The time would be required to design, license, and construct the facility and to develop the transportation infrastructure needed to move spent fuel from reactors to the facility. The DOE plans to complete some generic aspects of that development simultaneously with site-suitability studies for the repository. Therefore, deferring selection of the storage site until after the site-suitability determination might not add substantially to the *actual* time required to begin accepting significant amounts of spent fuel for centralized storage.

Characterization of Yucca Mountain during 1996 produced a great deal of scientific information which substantially improved the understanding of the site. Until recently, Yucca Mountain was thought to have very little water available at depth to affect repository performance. During 1996, analysis and synthesis of several types of data suggested that more water flows through the proposed repository level than was previously expected. A key issue to be addressed in 1997 will be further evaluating the amount of water present, its distribution in time and space, and its significance in evaluating the suitability of the site.

The safety of a proposed repository can be assessed by using a total system performance assessment (TSPA), that is, a predictive model of the repository's ability to contain and isolate waste. TSPA will play a major role in evaluating the merits of the Yucca Mountain site, from the 1998 VA through site recommendation and licensing in the next century. In contrast to past applications, particular emphasis will be placed on whether the TSPA demonstrates that the proposed repository complies with regulatory standards. This emphasis will place new demands on performance assessment, especially for ensuring the validity and transparency of its assumptions.

Although there is no formal requirement that the public accept the TSPA, to proceed without acknowledging the importance of such acceptance is condescending at best and a prescription for failure at worst. The likelihood of public acceptance of a TSPA will be significantly affected by its transparency. If the perception is that the TSPA is like a large black box whose results can be dictated by some manipulator arbitrarily adjusting hidden knobs, then no matter how good the underlying rationale, public acceptance will not be attainable.

Designing the repository and waste packages is an essential starting point for developing all four components of the VA. Although there is no need to have the designs optimized at the time of the VA, they should be integrated and contribute to waste isolation. New technology elements of the designs (if any) should be identified, and the necessary research, development, and demonstration programs should be described and the costs estimated. If existing technologies can be used in lieu of developing new ones, especially ones involving remote operations, their merits should be examined as part of the VA.

A key assumption of the DOE's concept for underground operations is that there will be no human entry into an emplacement tunnel when it contains spent fuel or high-level waste. Excluding humans means that all operations must be performed remotely. The Board has concerns about the dependability of a remotely operated system, especially the delays, costs, and safety in recovering from mechanical breakdowns or other events. This scheme probably can be implemented, but it may add unnecessary complexity and cost to repository development. In any case, it will require a program for developing and demonstrating equipment for spent fuel and high-level waste operations.

The Board believes that alternative concepts for underground operations should be developed and examined. This should begin immediately so that any alternatives that appear feasible and practical may be considered in the VA. At least one of the alternatives should be based on conservative application of existing technology, for example, shielding the waste packages so that human activity near them is possible and ventilating the emplacement tunnels to provide temperatures low enough for effective functioning of humans and machines, sensors, and other equipment.

Several years ago, the DOE assembled a single set of design assumptions that did *not* include alternatives such as backfill in waste-emplacement tunnels or low thermal loading. Now, any consideration of alternatives is treated as an "add-on" modification to the existing design. Not surprisingly, when alternatives are investigated as add-ons to the existing design rather than as features of designs that are integrated with the alternatives, they often are found to be prohibitively expensive. A credible analysis should be made of design alternatives (e.g., need for backfill) that may lead to fundamentally different repository designs.

An important element in designing and constructing the underground repository is ground support for the waste emplacement tunnels. Providing and maintaining stable tunnels for waste emplacement will be a major item in the cost of the repository. After the repository is closed, the waste packages are to provide containment for "thousands of years." Early collapse of the waste emplacement tunnels during the post-closure period could alter the assumed environment for, and integrity of, the waste packages and introduce an additional uncertainty in the expected containment period. Precast or cast-in-place concrete liners are alternatives to the steel sets used for ground support in the exploratory studies facility, and they offer advantages for long-term stability of repository tunnels.

The Board strongly endorses the concept of "defense-in-depth" for isolating radioactive wastes in a repository. Defense-in-depth can be achieved by using multiple and redundant individual barriers that have safety-performance attributes that are affected by different mechanisms or events. Adding barriers to ensure the integrity of the repository would seem to be a prudent move.

Comprehensive studies of fillers, drip shields, and engineered inverts are now warranted. The studies should in-

clude examination of the changes in design and operation of repository surface and underground facilities that would be necessary to accommodate efficient and effective use of fillers, drip shields, and engineered inverters as additional barriers. The studies also should examine the effect of additional barriers on total system performance and cost.

Recommendations of the Board

The recommendations in this report are summarized below. The Board makes the recommendations in the belief that they will help the DOE evaluate the suitability of the Yucca Mountain site for developing a repository and thereby achieve an important step in safely managing the nation's spent nuclear fuel and high-level waste.

- A decision to locate the nation's primary centralized storage facility for spent fuel at or near Yucca Mountain should be deferred until the suitability of the site as a repository location has been determined.
- To the extent possible under the market-driven initiative, efforts to develop storage and transportation casks should retain the advantages (e.g., standardization) previously offered by the multipurpose canister concept.
- Before making a determination of the suitability of the Yucca Mountain site for a repository, the DOE should complete additional studies of the area west of the current exploratory studies facility, where wastes would be emplaced, to determine its geologic, hydrologic, and geochemical properties. The best way to obtain the needed information is excavation of a tunnel westward across the proposed repository block.
- The DOE should make a concerted effort to ensure that future TSPAs are transparent and valid, that uncertainty is treated properly, and that any peer review of performance assessment or elicitation of expert judgment is objective.
- The DOE should consider ways of increasing public understanding and acceptance of TSPAs. One possibility is to establish processes, modeled on the lines suggested in a recent report by the congressionally chartered Commission on Risk Assessment and Risk Management, for involving and engaging the public.
- The DOE should develop and examine alternative concepts to the proposed remote underground repository operations, for example, ventilation of emplacement tunnels and shields for waste packages. Some alternatives should be developed in time for consideration in the viability assessment.
- The DOE should evaluate alternative design assumptions to determine whether enhanced repository performance or improved operations can be achieved cost-effectively.
- The DOE should evaluate the use of precast or cast-in-place concrete tunnel liners to achieve adequate long-term tunnel support. The evaluation should consider cost and possible effects on waste isolation.
- Given the inevitable uncertainties about repository performance, more attention to defense-in-depth (multiple, redundant barriers) is needed in the waste package and repository designs. In particular, *comprehensive* studies of alternative engineered barriers — such as fillers, backfill materials, drip shields, and engineered inverters — should be completed.

Introduction

The federal government, specifically the U.S. Department of Energy (DOE), is responsible for the long-term management and disposal of commercial spent fuel from nuclear power plants and of spent fuel and high-level radioactive wastes generated by the federal government, primarily in defense activities. A broad international consensus exists that high-level radioactive materials can be safely disposed of deep underground in a mined geologic repository. This has been and continues to be U.S. policy. A combination of engineered and natural barriers would isolate wastes from the accessible environment for thousands of years. During that time, radioactive decay would help to reduce the hazard of the wastes so that any releases to the environment would be at levels below regulatory concern. The 1982 Nuclear Waste Policy Act (NWPA) established a national road map for developing a repository, complete with timetables for major actions and investigations of multiple candidate repository sites. The act was amended in 1987 (NWPAA) to restrict site-suitability studies to a single candidate site at Yucca Mountain in Nevada. Studies of the Yucca Mountain site have dominated the DOE's management activities for civilian spent fuel and high-level waste since 1987.

Spent fuel and high-level wastes are very radioactive, long-lived, and potentially hazardous to humans and the environment. Predicting a repository's ability to isolate radioactive materials for thousands of years poses a major technical challenge. Detailed and expensive studies of the Yucca Mountain site were designed to meet that challenge. It is important that the right studies are carried out, that the scientific work is of the highest quality, and that the quality of the work can be demonstrated in an adversarial licensing process. Only if the Yucca Mountain site is adequately studied by using state-of-the-art scientific techniques can scientists, engineers, regulators, and the public, especially the citizens of Nevada, develop a sense of confidence that a repository will be safe for the thousands of years that spent fuel and high-level wastes will remain hazardous.

In the 1987 amendments to the NWPA, the Congress created the Nuclear Waste Technical Review Board (NWTRB — see text box, next page), an independent federal agency charged with evaluating the scientific and technical aspects of the U.S. spent fuel and high-level waste management program. The Board submits its findings, conclusions, and recommendations to the Congress and the Secretary of Energy at least twice each year. The DOE responds to the Board's recommendations in writing, and the responses are published in a subsequent Board report.

This report reviews programmatic developments and Board activities during 1996. Chapter 1 is an overview of the entire program, written for a general audience. It summarizes progress in 1996, especially in characterizing the Yucca Mountain site, and presents the Board's views on the status of the program at year-end. During 1996, analysis and synthesis of data indicated that more water flows through the proposed repository level of Yucca Mountain than was previously expected. Because water is so important in predicting the long-term performance of a desert-sited repository, Chapter 2 reviews hydrologic issues in some detail, along with issues related to predicting the performance of the overall repository system. Chapter 3 discusses design of waste packages and repository facilities. The Board believes that design issues will be of increasing importance in predicting repository performance. Finally, Chapter 4 summarizes Board activities during 1996.

The Board's first report (NWTRB 1990) was released in March 1990. All board reports are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402, or from the Board's office in Arlington, Virginia.

Purpose of the Nuclear Waste Technical Review Board

“The purpose of the Board is to provide a source of independent expert advice to DOE and the Congress on technical issues and to review DOE’s efforts to implement the nuclear waste program. The Board has no authority to require the Department to implement its recommendations, but it is assumed that the Department will heed those views or clearly state its reasons for disagreeing. The Board will provide valuable assistance to the Congress in determining whether the DOE’s activities have solid technical foundations.”

(U.S. Congress. House 1987)

Functions and Duties of the Nuclear Waste Technical Review Board

“The Board shall evaluate the technical and scientific validity of activities undertaken by the Secretary [of Energy] after the date of the enactment of the Nuclear Waste Policy Amendments Act of 1987, including:

- (1) site characterization activities, and
- (2) activities relating to the packaging or transportation of high-level radioactive waste or spent fuel.”

“The Board shall report not less than 2 times per year to Congress and the Secretary [of Energy] its findings, conclusions, and recommendations.”

(NWPAA 1987)

Nuclear Waste Technical Review Board Powers

“The panel is given very strong powers to obtain information from the Department. Of course, laws such as the Privacy Act which prohibit disclosure of information in certain circumstances would apply. It should be remembered that the panel is created as an establishment in the executive branch, and that its value can only be achieved if the Secretary makes all information available on a timely basis. The provision relating to draft documents makes clear that the Secretary may not refuse to provide documents with the excuse that they are merely drafts. The Board’s effectiveness is dependent upon its ability to affect actions of the Secretary while they are happening, and not just after the fact.”

(U.S. Congress. House 1987b)

Chapter 1

Program Overview

A New Program Plan

In 1996, the DOE released a revised program plan (DOE 1996a), the key features of which are summarized below.

Viability Assessment

The DOE's revised Program Plan officially introduced a new program milestone, the viability assessment (VA). The VA is to be completed by September 30, 1998. According to the DOE (DOE 1996d), the viability assessment will include four components: "(1) the preliminary design concept for the critical elements for the repository and waste package; (2) a total system performance assessment, based upon the design concept and the scientific data and analysis available by September 30, 1998, describing the probable behavior of the repository in the Yucca Mountain geological setting relative to the overall system performance standards; (3) a plan and cost estimate for the remaining work required to complete a license application; and (4) an estimate of the costs to construct and operate the repository in accordance with the design concept."

Appearing before the Board at its October 1996 meeting, the director of the DOE's Office of Civilian Radioactive Waste Management, Dr. Daniel Dreyfus, characterized the VA in this way (DOE 1996d):

It is a management tool for the program and a major informational input to the policy process. . . . It will focus the final years of the site investigation and facility design on the important uncompleted work and the unresolved issues, and it will provide all participants with a frame of reference for their evaluation of the project . . . The viability assessment will give all participants a better comprehension of the repository venture and the significance of the data then available. It will also give policy makers information about the probability that a repository is a viable undertaking.

Dr. Dreyfus emphasized that the VA is "just a step along the way" to the more formal and consequential DOE Secretary-level decision on whether to recommend the Yucca Mountain site to the President for development as a repository.¹ The fiscal year 1997 appropriations bill (U.S. Congress 1996) endorsed the VA concept and directed the DOE to complete the VA by September 30, 1998.

The Board believes that a VA can serve an important function in focusing and integrating the program and, when needed, adjusting its course. For example, the Board strongly supports the DOE's decision to develop a specific, although conceptual, design of "critical elements" of a repository for use in estimating costs and assessing performance. This relatively new emphasis on the engineering and operational aspects of a repository is a positive change in the program.

The Board realizes that the planned VA may trigger significant decisions such as selecting the location of a centralized facility for storing spent fuel. The VA may be used in ways that attach more significance and substance to it than may be warranted. Understanding the VA's technical limits is important. The VA will be based on preliminary repository and waste-package designs and will be supported by incomplete site-characterization data. Scientific and technical information will be missing, especially from within the area where wastes would be emplaced, that will be required for a determination of site suitability and a recommendation to the President for developing a repository.

The technical limits of the VA can be compensated for to a degree. The models used in a performance assessment can be constructed conservatively. Bounds can be placed on

¹ The DOE does not plan to judge whether the repository system it has designed is "viable," at least not as a formal decision that could be legally challenged. Instead, the DOE will develop the information needed for the Congress to assess viability when considering continued funding for the program.

the parameters and distributions that are used to predict performance. Sensitivity analyses can be carried out to understand the key variables affecting whether the repository system will contain and isolate waste. Still, the VA will be a preliminary assessment that is based on an incomplete investigation of the site and a very preliminary design. The Board urges caution in drawing premature conclusions about the suitability of Yucca Mountain from the VA.

Site Recommendation

According to the DOE's schedule (DOE 1996a), about three years will pass between the VA and a site recommendation. During that period, many investigations will yield critical information and additional performance assessments will be completed. The investigations include tunnel-scale heater experiments for better estimating how water moves around hot waste packages and corrosion tests on waste-package materials. The DOE also needs to complete a better assessment of current moisture and seepage through the potential repository location. This information will help determine whether a repository should be developed at Yucca Mountain. However, the decision on whether to recommend development of a repository also will depend strongly on the likelihood of compliance with applicable regulatory criteria. The criteria are expected to change in the near future, as discussed in the following sections.

Revision of the DOE's Siting Guidelines

The NWPA instructed the DOE to develop general guidelines for recommending sites for development as a repository. The NWPA specified the site properties or characteristics, such as hydrology, seismic activity, and proximity to water supplies, to be addressed in the guidelines. With the concurrence of the Nuclear Regulatory Commission (NRC), the DOE published its guidelines in November 1983 (10 CFR 960).

Recently, the Congress signaled the DOE that it is less interested in the DOE's site-suitability decision than in determining whether to submit a license application for repository construction.² Accordingly, the DOE proposed to revise its siting guidelines by inserting a new section

applicable only to Yucca Mountain (DOE 1996e). For long-term isolation of wastes, judgments about the site are to be based on the site's conformity to the standard for public health and safety set by the U.S. Environmental Protection Agency (EPA) and implemented by the NRC. Conformity will be established using mathematical models,³ i.e., through a "performance assessment." Along with a final environmental impact statement and a refined repository design, compliance with the revised siting guidelines will determine whether the Secretary of Energy recommends the site to the President and, subsequently, whether the DOE submits an application to the NRC for constructing a repository. The DOE plans the site recommendation for 2001.

Safety Standards for Yucca Mountain

Changes in the basic safety standards for a Yucca Mountain repository are being considered as directed by the Congress in the Energy Policy Act of 1992. That law directed the EPA to contract with the National Academy of Sciences (NAS) to recommend the scientific bases for developing standards. The EPA was charged to promulgate health and safety standards for the Yucca Mountain site that are *based on and consistent with* the NAS recommendations.

The report, *Technical Bases for Yucca Mountain Standards* (NAS/NRC 1996a), released on August 1, 1995, recommends risk-based standards that emphasize protecting individual members of the public. The report also recommends that institutional controls not be relied on as the means of preventing unacceptable exposures to releases from a repository. Furthermore, the report finds that there is no scientifically supportable way to predict the probability of future human intrusion. The report recommends that performance standards for a Yucca Mountain repository apply for a time limited only by "the long-term stability of the fundamental geologic regime — a time scale that is on the order of 1,000,000 years at Yucca Mountain." The report stated that many of the details related to the standards involve making public-policy choices that can be illuminated by, but not determined by, science alone.

For some time, the Board has believed that current U.S. regulations and, perhaps, the health and safety standards

² Legislation considered by the Congress during 1996 would have revoked the DOE's siting guidelines and directed the DOE to proceed toward licensing the Yucca Mountain site without a suitability determination (U.S. Congress. Senate 1996).

³ Presumably, the models will estimate uncertainties in repository performance, allowing judgments about the likelihood that compliance with the standard will be achieved.

governing spent-fuel disposal need to be updated. The current EPA health and safety standard and the NRC and DOE regulations were too detailed and enacted too early in the process of searching for a permanent repository site. Scientific and technical knowledge, particularly when applied to a first-of-a-kind undertaking, takes time to evolve. In retrospect, the wiser course may have been to assemble that knowledge and use it in developing a regulatory framework. The Board believes that the current scientific and technical understanding of the conditions at the Yucca Mountain site should establish a sound technical basis for revising safety standards and regulations. The EPA reportedly is close to releasing a draft revision of its safety standards. The Board has kept abreast of the issues involved in developing the standards and plans a thorough review of the draft standards when they become available.

Implications for Spent-Fuel Storage

The timing of the VA and the site recommendation has important implications for a possible decision to develop a centralized spent-fuel storage facility. The Board noted that there are technical advantages to locating a storage facility at or near a repository site (NWTRB 1996b). If Yucca Mountain is developed as a repository, a storage facility will be needed nearby to support repository operations. However, if Yucca Mountain is not suitable as a repository site, it might not be the best location for centralized storage of spent fuel. The cost of constructing and operating the overall spent fuel management system (transportation, storage, and repository) can be improved if selection of a location for a centralized storage facility for the majority of commercial spent fuel is deferred until the suitability of Yucca Mountain as a repository location has been determined.

At the Board's October 1996 meeting (NWTRB 1996c), Dr. Dreyfus estimated that about four years would elapse between selection of a site for a centralized storage facility and the first receipt of commercial spent fuel there. The time would be required to design, license, and construct the facility and to develop the transportation infrastructure needed to support the facility. The DOE plans to complete some generic aspects (especially design work and procurement of transportation services) of storage facility development simultaneously with repository site-suitability studies. Therefore, deferring selection of the centralized storage site until after the repository site-suitability determination might not delay substantially the *actual* time for accepting significant amounts of spent fuel for centralized storage.

The DOE's Market-Driven Initiative for Transportation

The revised *Program Plan* (DOE 1996a) assumes that the Congress will designate a site for a centralized spent-fuel storage facility in 1999. In anticipation of this possibility and the consequent need for a transportation capability, the DOE launched its "market driven" initiative for transportation of spent fuel from the utility reactor sites to the central facility. The philosophy underlying this initiative is reliance on the private sector for transportation services. The DOE's role is limited to purchasing a satisfactory service. The broad conceptual outline of this initiative was first presented to the Board at its April 1996 meeting, and later was announced in the *Federal Register* (DOE 1996b). The *Federal Register* announcement was followed by a "pre-solicitation" conference of interested parties on July 9.

The DOE concept is to divide the nation into four regions. A contractor for each region will, observing applicable regulations, transport the spent fuel from all of the reactors within that region to the central facility. The contractors will furnish all needed equipment and capabilities, including casks, rail or truck carriage, and equipment for intermodal transfer and heavy-haul capability. The DOE will pay for the service on a per-unit basis. In essence, the contractors will be responsible for almost everything, including acquiring and maintaining all equipment, working with utilities to persuade them to strive for system efficiencies (which may require modifying some of the terms in the standard contract that they have with the DOE), and working with the states and localities on issues of concern to them. The contractors will act as agents of the DOE in accepting the waste and will be responsible for the waste until it is delivered to the central facility. The DOE, however, plans to retain the responsibilities mandated under Section 180 (c) of the NWPA: providing financial and technical assistance to the states for enhancing safety along the transportation routes, including emergency response.

This philosophy of near-total reliance on the private sector contrasts sharply with the DOE's previous plans for transportation. Until this initiative, the DOE had assumed the role of developer and provider of both the waste packages and the transportation services. In the previous *Program Plan* (DOE 1994), DOE policy was to develop the multi-purpose canister (MPC) concept. The MPC was to be a single container within which spent fuel would be sealed

for storage at nuclear power plants, transportation to a centralized storage facility or a repository, and eventually final disposal. The DOE would have been responsible for developing and producing the MPC and the related transport casks, as well as for transport and transport-related services, such as cask maintenance. In fiscal year 1996, congressional direction and sharp budget reductions terminated development of the MPC. The Board is disappointed by the termination of the MPC development effort, which would improve both the efficiency and the safety of the overall system for managing and disposing of spent fuel. The Board hopes that many of the advantages of the MPC concept (e.g., standardization) can be retained as the market-driven initiative develops.

Some major (largely nontechnical) issues need to be addressed and resolved before this concept of turning over transportation responsibilities to the private sector can become an operating reality. One is the large financial risk that would be faced by the contractors. The contractors must develop all of the necessary transportation capability and acquire all of the equipment needed to provide a specified level of service. But, they would be paid only for services performed. If the volume of spent fuel to be shipped is smaller than expected, the contractors' investments would be at risk. This issue was not addressed in the initial version of the market-driven concept but may be part of the negotiations as the concept develops.

Another issue is who will make decisions about the major institutional and policy questions associated with transporting spent fuel and how they might be resolved. Examples of policy issues of concern to state and local government officials are routing decisions and the criteria adopted for making the decisions. In the initial version of the market-driven concept, most of the responsibility, with the notable exception of the Section 180 (c) requirement, seems to be left to the contractors, as are almost all interactions with the public and with state and local governments.

Although the health and safety risks in transporting spent fuel are low, various elements of the public perceive them as a major issue. It is important, therefore, that the institutional issues be anticipated and addressed to ensure the smooth and safe running of a large-scale, long-term transportation operation.

In response to the May *Federal Register* notice on its transportation needs (DOE 1996b), the DOE has received initial comments on these and other issues. The next step is preparation of a draft request for proposals. Publication is expected early in 1997.

Design and Safety Analysis for a Generic Storage Facility

The DOE has begun the design and safety analysis for a non-site-specific centralized storage facility. As part of this effort, the DOE intends to prepare a safety analysis for the generic facility for submittal to the NRC in May 1997.

The generic facility would have an ultimate capacity of 40,000 metric tons of uranium (MTU)⁴ and would be designed to be licensed for 100 years. It would be developed in two phases. During phase I, the facility would accept fuel only in canisters. Spent fuel in bare assemblies would not be accepted until phase II. In phase I, the spent fuel would be sealed in canisters at the reactor sites and placed in temporary on-site storage modules. Later, the fuel would be transported to the storage facility in a transportation overpack, or cask. This storage-transportation combination concept is referred to as "dual purpose" because the storage canister can be loaded directly into its transport overpack without being reopened. Phase II operations could be similar, or, as an alternative, bare spent-fuel assemblies could be removed from transportation-only casks in a hot cell and loaded into a different waste package for storage.

The safety analysis that the DOE is preparing is only for phase I. The report will describe a non-site-specific storage facility and its concept of operations. The report will assume that dual-purpose technology will be available when needed — that is, NRC-certified storage and transport container systems will be available in the private sector when the facility becomes operational. The report will assume the features of the designs now being developed by several vendors that have submitted applications for certification to the NRC. Because of the assumption that the container systems will have been certified by the NRC, the DOE safety report will not include the safety case for them. The major emphasis of the report will be on the characteristics of the generic (unknown) site itself and the facility to be built on it. The analysis will establish a list of site-related criteria and develop acceptable bounds, or limits, for many of them, which then can be applied to a specific site when it is identified. Examples of these crite-

⁴ MTU is a measure of the quantity of spent fuel. About 2,000 MTU are generated each year, and the cumulative inventory projected from all existing nuclear power plants in the United States over their design lives is about 85,000 MTU.

ria include ambient temperature range, wind loads, snow and ice loads, seismicity, and precipitation. Bounds for some will have to await the selection of the site.

Under the current regulatory scheme (in 10 CFR Part 72), the NRC will certify surface storage containers for 20 years, at-reactor storage facilities for 20 years, and centralized storage facilities (referred to specifically as “monitored retrievable storage facilities” in Part 72) for 40 years. There are provisions for renewing all of the certifications. The NRC has determined that spent fuel can be stored safely for at least 100 years. Nonetheless, a 100-year initial licensing period, as called for in some bills considered in Congress in 1996, extends the typical licensing time for storage. As the Board noted in its report on interim storage of spent fuel (NWTRB 1996b), few data on the very long-term effects of storing spent fuel in dry casks have been gathered so far. Limited data exist on the effects of prolonged storage on subsequent long-term integrity of fuel elements, fuel assemblies, or canisters in a repository, but there are no data for storage periods on the order of 100 years or longer. The DOE has sponsored research at Idaho National Engineering Laboratory on the effects of long-term storage, and work was performed earlier at Sandia National Laboratories.

Status of the Program

Progress in studying the Yucca Mountain site is encouraging. The program is collecting information from the proposed repository level and surface area that will help determine the suitability of the site. In general, the Board believes that the ongoing and planned studies are appropriate for producing the information needed to support the VA, the site recommendation, and the license application. The principal exception is the need to obtain more geologic, hydrologic, and geochemical information from the area west of the current exploratory studies facility (ESF) where waste would be emplaced.

Waste Isolation Strategy

The Board was pleased with the progress made in 1995 in formulating a waste isolation strategy and in using the strategy to help set priorities for the activities of the Yucca Mountain project. During 1996, however, development of the waste isolation strategy slowed. Dr. Dreyfus noted in his September 4, 1996, presentation to the NRC (DOE 1996c) that people working on the Yucca Mountain project are finding it difficult to reach a consensus on the need for specific lines of scientific and engineering work. How-

ever, he also reported that efforts to develop a consensus were promoting greater integration and a more intense scrutiny of the technical rationale for proposed work. Improved integration and development of better priorities have long been called for by the Board. Therefore, the Board is satisfied that the goal of articulating a clear waste isolation strategy seems to be serving its purpose. Additional efforts will be needed in the coming year to continue developing the strategy and to ensure that it is used to develop the technical bases for planning program activities. Further refinement of the strategy will likely be needed beyond the VA as additional site data are acquired.

Program Schedules

Despite the sharp reduction in funding for fiscal year 1996, the program tried to maintain nearly the same schedules for repository development and licensing. For example, a major goal of the DOE’s 1994 *Program Plan* (DOE 1994) was a “technical site-suitability” decision⁵ in 1998. The DOE now says that funding limits will not allow such a decision by 1998. The DOE’s response has been to maintain a 1998 milestone of more limited content and give it a new name — “viability assessment.” The technical basis for the VA will be less complete than anticipated for the technical decision on site suitability.

Evaluating Site Suitability

Perhaps the single most important technical decision facing this program is determining the suitability of Yucca Mountain as a site for a repository. For the next two years, the program will focus on a VA of the site. The Board believes that the VA will not provide adequate information for that decision. Rather, it is an assessment that the site continues to be a candidate that requires additional study, leading to a determination of whether it is suitable to be recommended to the President for repository development in 2001.⁶ Nothing has been found to date to indicate that the site is unsuitable.

⁵ The technical site-suitability decision would have evaluated the Yucca Mountain site against all the siting guidelines of 10 CFR Part 960 except the guidelines for environmental, socioeconomic, and transportation issues.

⁶ The process of evaluating site suitability would begin with publication of a technical report documenting compliance with the DOE’s siting guidelines in 1999. After reviews within the DOE, by the NRC, and by the public, the Secretary of Energy would recommend to the President in 2001 that a repository be developed at the site.

The DOE believes that additional studies beyond those planned for the VA will be needed to evaluate the site's suitability (DOE 1996d), and the Board agrees. More information is needed on the geologic, hydrologic, and geochemical properties of the repository-level rock to confirm that a repository of useful size can be sited there. A major concern is the magnitude and distribution of the water flow, particularly in the proposed emplacement area to the west of the existing main tunnel. A small tunnel extended across this area is needed to observe water flow, as well as the rock structure, in this unexplored region. The Board concludes that such exploration and observation should be completed prior to the site suitability evaluation.

Another important issue to be assessed prior to completing the site-suitability evaluation is the thermal effect of the emplaced waste on water and vapor flow. Significant information will be gained from the tunnel-scale thermal tests, which the DOE has begun. The tests cannot be completed and the results evaluated before the 1998 VA, but they should be available for a license application in 2002.

Important Areas for 1997

Three areas of study — hydrology and radionuclide transport, performance assessment, and design — will form the foundation for the 1998 VA and the subsequent evaluation of the suitability of the Yucca Mountain site. The major issues in each area are discussed in detail in the next two chapters of this report and are summarized below.

Hydrology and Radionuclide Transport

Movement of water into and through a repository is the primary mechanism by which significant amounts of radioactive material can be released to the accessible environment. Water entering a repository can corrode waste packages, dissolve or leach radionuclides from the waste, and carry them downward to the water table. The contaminated water then can flow horizontally to the environment.

Because water is recognized as the primary mechanism for mobilizing and transporting radioactive material, it is important to know *where, how much, and how frequently* water might enter a repository and *how fast* the water can travel from the repository to the environment. Infrequent, small amounts of water may be unimportant, as may be water that moves so slowly that radionuclides can decay

or be diluted to harmless levels before reaching the environment. At Yucca Mountain, however, fractures and faults may provide fast flow paths that allow water to move downward from the surface very rapidly, especially after infrequent periods of high rainfall. If a repository is developed at Yucca Mountain, identifying or anticipating fast pathways within the repository block will be important so that they can be avoided or mitigated when emplacing wastes. If evidence is found that significant volumes of water are moving through many fast flow paths and will contact waste packages, the site may prove unsuitable for developing a repository. The Board believes that determining the existence and abundance of fast flow paths can best be accomplished by excavating an east-west tunnel through the potential repository block west of the existing ESF. This tunnel would allow direct observation of fractures and collection of rock and water samples for isotope studies. It also would allow observation of ambient moisture conditions within the potential waste emplacement area. Ventilation of the ESF now removes large amounts of water from the surrounding rock, drying the rock and making it difficult to accurately identify possible fast flow paths. An alcove or portion of tunnel should be sealed off from the perturbing effects of ventilation, allowing more realistic observations of ambient moisture conditions.

Characterization of Yucca Mountain during 1996 produced a great deal of scientific information which substantially improved the understanding of the site. Until recently, Yucca Mountain was thought to have very little water available to affect repository performance. During 1996, analysis and synthesis of several types of data suggested that more water flows downward to the proposed repository level than previously expected. A key issue to be addressed in 1997 will be further evaluating the amount of water present, its distribution in time and space, and its significance in evaluating the suitability of the site.

Performance Assessment

The safety of a proposed repository can be assessed by using a total system performance assessment (TSPA), that is, a predictive model of the repository's ability to contain and isolate waste. TSPA will play a major role in the evaluating the merits of the Yucca Mountain site, from the 1998 VA through site recommendation and licensing in the next century. In contrast to past applications, particular emphasis will be placed on whether the TSPA demonstrates that the proposed repository complies with regulatory standards.

The degree of confidence that can be placed in mathematical models of performance will be influenced by several factors, including the following:

1. *Transparency.* Technical and nontechnical audiences need to understand the performance-assessment process. Key assumptions underlying the models and the analyses they support must be made explicit and understandable.
2. *Treatment of uncertainties.* Uncertainties are unavoidable in long-term projections of repository performance. All important uncertainties need to be identified and addressed so that their influence on estimates of repository safety can be evaluated and incorporated in a performance assessment.
3. *Validity.* To the extent possible, the validity of repository performance assessment models must be established. Examining engineered and natural analogues, along with simplified calculations, can increase confidence that the repository will perform as expected. Using outside expertise for conducting independent peer review and eliciting expert judgment also will help to establish the validity and credibility of the results.
4. *Public acceptance.* Public acceptance of performance assessment can be increased by transparency and by ensuring adequate opportunities for public involvement. If a performance assessment is perceived as reaching a foregone conclusion, public acceptance will suffer.

Design

As characterization of the Yucca Mountain site advances, developing the logistics and design of a potential repository's surface facilities, underground facilities, and engineered barrier system becomes important. Evaluating the viability (and, subsequently, the suitability) of the Yucca Mountain site will require having a clear concept of the types of facilities that will be constructed there, their functions, and the operations to be performed within the facilities.

1. *Functional design.* Specifying the functions of the engineered component of the repository system is the most fundamental, and one of the most important, steps in the design process. Because this step is so important, the Board believes that the DOE should evaluate alternative functional specifications to determine their effects on the design, construction, and operation of a repository system. For exam-

ple, alternative engineered barriers should be considered that might divert water from wastes, protect waste packages from rock falls, or modify the geochemical environment of the waste packages.

2. *Construction planning.* More than 100 miles of tunnels may have to be excavated to emplace the spent fuel and high-level wastes in a Yucca Mountain repository. This compares with the 5 miles excavated for the ESF. Excavation efficiency must be improved beyond that demonstrated in constructing the ESF, or the cost of repository construction may be exorbitant.

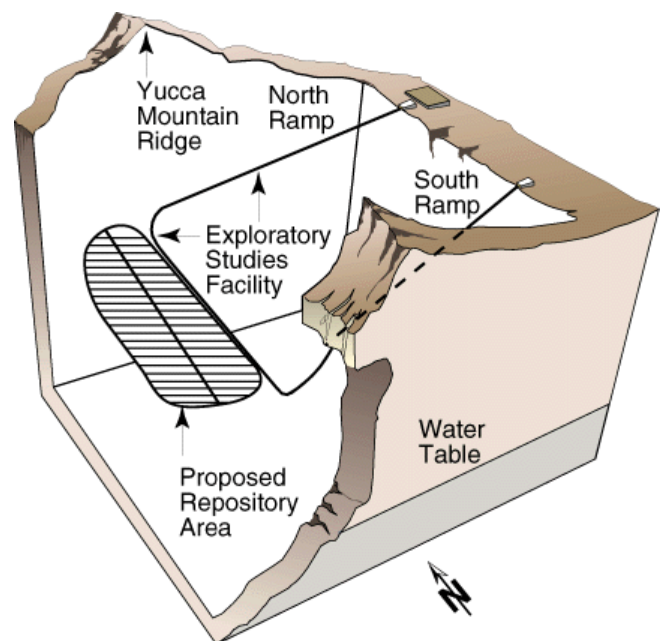


Figure 1. Schematic of ESF (DOE drawing)

3. *Operations.* Operations at a Yucca Mountain repository involve more than merely disposing of wastes. Operations include maintaining the ability to retrieve wastes for 100 years and conducting scientific studies to confirm predictions of long-term repository performance. Several aspects of repository design, especially maintaining the stability of tunnels, will be affected by the length of the projected operating period. Presentations at the Board's October 1996 meeting (NWTRB 1996c) indicated that the DOE is becoming more aware of the issues associated with repository operations, some of which are discussed in Chapter 3 of this report.

Progress in Exploration and Testing

Surface-based testing at the Yucca Mountain site, including geologic mapping and geologic sampling from boreholes, has been conducted for several years, as has testing at laboratories located away from Yucca Mountain. More recently, the DOE has been excavating the ESF, which is illustrated schematically in Figure 1.⁷ The ESF provides access to the geologic formations within which a repository might be built. There, scientists can collect detailed samples and observe directly the geologic and hydrologic conditions that may influence long-term waste isolation. Information acquired from the ESF will be combined with information from surface-based studies, laboratory testing, and engineering design features to determine whether a repository at the Yucca Mountain site would safely isolate wastes from the accessible environment.

tion and sampling of geologic and hydrologic conditions. An extension of the tunnel (south ramp) is being excavated in an easterly direction from the repository level back to the earth's surface. Several rooms ("alcoves") were excavated along the north ramp and the main drift to provide underground locations for scientific testing.

Excavating the ESF

The ESF was excavated with a tunnel boring machine (TBM), which functions like a very-large-diameter (7.6 meters or 25 feet) drill bit. Excavation of a tunnel using a TBM is generally faster than using drill-and-blast methods and should be cheaper. As important, it causes less damage to the surrounding rock. The primary purpose of the ESF is to enable scientists to sample, observe, and study directly the properties of the rocks in which a re-

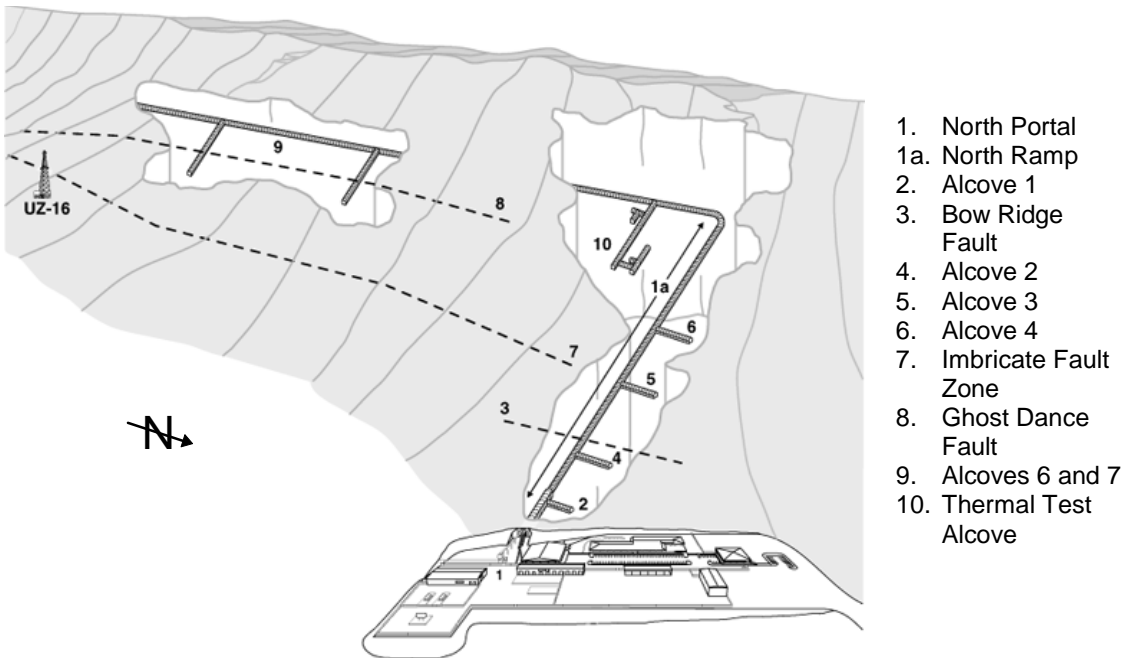


Figure 2. Features of the Exploratory Studies Facility (DOE drawing).

Figure 2 shows the main features of the ESF. The ESF consists of a tunnel (north ramp) extending to the west from the earth's surface down to the depth beneath Yucca Mountain where a repository would be built. At the candidate repository depth, a north-south tunnel (called the "main drift") was excavated through the rock, allowing observa-

tion and sampling of geologic and hydrologic conditions. Minimizing damage to the rock is therefore a significant consideration, as is obstructing access to the rock surface when ground support is installed.

By the middle of October 1996, the TBM had completed the main drift, rounded the turn toward the south ramp, and entered the geologic unit just above the level of the potential repository. The 3-kilometer (10,000-foot) north-south traverse of the Yucca Mountain geologic block required approximately one year to excavate and stabilize

⁷ Figures 1 and 2 suggest that the main ESF tunnel ("main drift") lies directly below the crest of Yucca Mountain. Actually, the main tunnel and much of the proposed repository area lie to the east of the crest, as illustrated in Figure 4 on page 18.

with ground support. During that time, construction also was started on an alcove for thermal testing and on two alcoves for exploring the Ghost Dance Fault, as illustrated in Figure 2. Excavation of the remaining part of the south ramp should be completed early in 1997, barring unanticipated slowdowns.

TBM Operations

The performance of the TBM varied widely from month to month, as shown in Figure 3. A factor contributing to slow progress may have been the north-south alignment of the main drift, roughly parallel to the major joint set (rock fractures). This alignment may have helped cause localized “fall-outs” of rock as the tunnel was excavated by the TBM. Later, when excavating the south ramp, regions of high fracture density added to rock instability around the TBM, requiring the time-consuming installation of heavy ground support.

The cost per meter of ESF construction was reduced during fiscal year 1996, an encouraging trend. The reduction is attributed to better management, improved cooperation between the DOE and the management and operating contractor (M&O), use of industry expertise by establishing a board of consultants, and a general maturing of the project. Nevertheless, excavation costs remain substantially higher than for comparable commercial projects, suggesting that there are additional opportunities for improving excavation efficiency and cost-effectiveness.

Dust Problems

Early in 1996, the DOE became aware of a potential safety problem: ESF excavation was producing high concentrations of silica dust in the air near the TBM. The dust resulted from cristobalite, a mineral abundant in the Topopah Spring geologic unit where a repository would be located. A specialist in dust control and ventilation was brought in to help measure dust quantities, identify the activities causing the dust, and develop mitigation measures.

By September, measurements indicated that dust levels exceeded the limits allowed by the Occupational Safety and Health Administration (OSHA). The DOE stopped excavation to allow full implementation of dust-mitigation efforts. Excavation then proceeded under the requirement that all workers in the tunnel wear full-face dust masks, which was a drain on worker productivity.

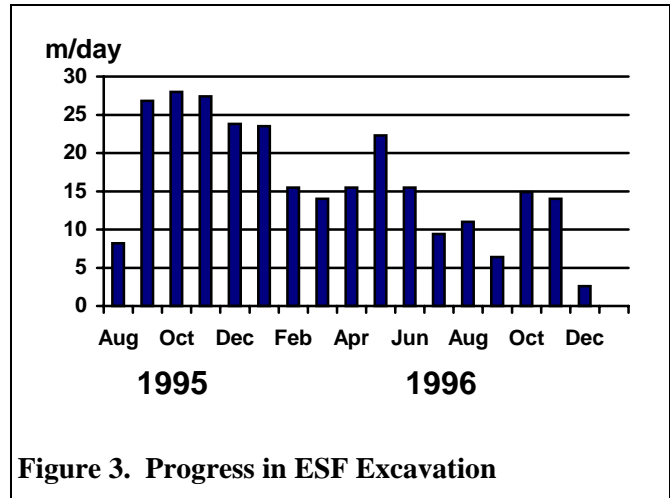


Figure 3. Progress in ESF Excavation

Board of Consultants

The ESF board of consultants was established in 1995 to advise the M&O on the safety and productivity of ESF engineering and construction activities. During 1995 and 1996, the consultants addressed problems encountered in excavating the ESF, contributing to the reduced costs and increased excavation efficiency discussed above. In June 1996, the board of consultants was asked to focus its attention on the conceptual design activities for the underground part of the repository.

The consultants’ recommended changes (Consulting Board 1996) to the repository conceptual design include (1) eliminating more than 11,000 meters (36,000 feet) of 9-meter (30-foot)-diameter “TBM launch mains” (i.e., tunnels used to start the operation and movement of a one-of-a-kind TBM); (2) using a standard TBM for excavating the waste emplacement tunnels; (3) providing spare emplacement tunnels for temporary storage of waste packages so that personnel can enter previously loaded tunnels for inspection or maintenance; (4) continuing to focus on repository ventilation considerations, particularly the means and methods required for controlling air flows through the emplacement tunnels; and (5) cautioning that the unique safety issues related to the large scale and complexity of the repository operation must be analyzed and addressed not only during the construction effort but also during the operation of the repository.

Alcove Excavations

Alcoves are excavated horizontally from the main ESF tunnel into the adjacent rock to establish locations for scien-

tific tests and to allow examination of rock properties. Excavation of an alcove called the “thermal test facility” was completed in 1996, and the initial phase of testing, called the “*in situ* single-heater thermal test,” was started in late August. Its primary purpose is to test instruments to be used in later thermal tests, but some information about rock properties also will be sought to support geomechanical design efforts. The heat-up phase will last about one year. The single heater is 5 meters (16 feet) long and has a thermal output of 4 kilowatts (kW). Near-field rock temperatures of up to 200°C (392°F) are expected. This will be the only repository-level test generating *in situ* thermal and hydrogeologic data for the DOE’s 1998 VA.

A second, larger-scale test, called the “drift-scale⁸ thermal test,” is to start in August 1997, and cool-down is to start two years later. The test will simulate a 55-meter (180-foot) length of waste emplacement tunnel, using a linear thermal loading of approximately 5 kW/meter (1.6 kW/foot). To speed up heating so that useful information can be developed in time for repository licensing, the thermal load is substantially higher than any thermal load that actually could be used in a repository. This test should produce important information about changes in hydrogeologic conditions as a repository heats up and later cools down again. Examples include initial dry-out and later rewetting of regions near the wastes, thermally driven buoyant flow of air and water vapor, and “refluxing” as vapor condenses and flows back toward the repository. In addition to hydrogeologic data, the drift-scale thermal test will provide quantitative data on the response of candidate ground-support structures and the rock itself to high temperatures.⁹

Two exploratory alcoves are being excavated to examine the properties of the Ghost Dance Fault, a major geologic feature of the site. The Ghost Dance Fault zone at the north alcove was explored in November 1996. Early data indicate that the fault zone starts 143 meters (470 feet) from the main drift and is approximately 11 meters (36 feet) wide at this point. The fault zone was located by excavating an exploratory tunnel 105 meters (345 feet) long and then drilling a horizontal borehole the remaining distance. No waste disposal would occur near this fault zone, but examination of the fault is expected to provide insights

into the geologic and hydrologic conditions in areas adjacent to where a repository might be constructed.

Excavation of the south Ghost Dance Fault access alcove was started in late October 1996. The expected length of the alcove is 125 meters (410 feet). As with the north Ghost Dance Fault alcove, a horizontal borehole will be extended an additional 20 to 30 meters (65 to 100 feet) to penetrate the fault zone.

Lessons Learned

During 1996, industry experts were used successfully to help solve ESF construction problems. The experience with the board of consultants, first in the ESF construction and now in the repository design, appears to have overcome initial DOE misgivings about the use of outside consultants. The DOE’s response to the dust problem, seeking outside expertise and counsel and acting on the advice, is commendable.

Excavating the ESF has allowed access to the potential repository level, where exploration and testing are producing a wealth of scientific information, as discussed in this report. Unfortunately, little information has been obtained from construction of the ESF that can be used to accurately predict the cost of excavating the many miles of repository tunnels. There are major differences between the present TBM operations in 25-ft-diameter tunnels and those anticipated for the smaller emplacement drifts. Significant reductions in cost and improvements in production should be achievable for the emplacement drifts by using management and contracting practices that provide incentives for cost-effective production and an integrated TBM and ground-support scheme that fits the ground conditions. Also, ground support conditions are anticipated to be much more favorable because of a significantly smaller tunnel diameter and the east-west orientation of the tunnels, which should cross, rather than run parallel to, the major rock fractures and faults.

Testing in the ESF

Underground Mapping

As the ESF is excavated, fractures and other geologic features are sketched and documented in a process called “mapping.” Mapping at the ESF level shows agreement with the new surface map (Day 1996) except for the presence in the ESF of a 1,000-meter (3,300-foot)-long frac-

⁸ The terms “drift” and “tunnel” are synonymous.

⁹ Competent ground support may be needed to prevent rock falls or tunnel collapse that would interfere with waste retrieval, could damage waste packages, or could affect waste isolation by altering the waste package environment.

ture zone in the south-central part of the repository block. The zone, called the “Broken Limb fracture zone,” consists of closely spaced,¹⁰ parallel smooth fractures that may be limited to the middle of the Topopah Spring formation (the proposed repository location). The fractures appear to be “communicating” with each other, as shown by an observed pneumatic response in a well at the south end of the zone while the TBM was still at the north end. Isotopic measurements (discussed below) indicate that continuity among some of the fractures also may serve as fast flow paths for water from the surface.

Isotopic Studies and Water Flow in the Unsaturated Zone

Infiltration is the part of the precipitation that enters soil or rock rather than running off into washes, streams, etc. Some of this water will be returned to the atmosphere by evaporation or transpiration of plants. Water that penetrates below the root zone into the mountain is called “net infiltration.” The amount of water entering and moving through the mountain is an important constraint for modeling the hydrology of the unsaturated zone. As the water moves downward through the mountain, it is redistributed because of the heterogeneous nature of the geology. The part of the net infiltration that eventually flows down through the repository level is called the “percolation flux.” The magnitude and spatial and temporal distribution of the percolation are the most important properties that affect waste isolation.

Studies of rock and pore-water samples from the site can indicate the residence time of water in the rock and the ages of the minerals filling fractures and voids at Yucca Mountain. The data have been vital in illuminating how water moves through the unsaturated zone of Yucca Mountain and, therefore, how well a repository would isolate radioactive waste from the environment. An important isotope studied at Yucca Mountain is chlorine-36 (³⁶Cl).

Chlorine-36 is formed naturally by cosmic rays interacting with natural chlorine, argon, and other materials in the atmosphere and at the Earth’s surface. It has a half-life of approximately 300,000 years. Atmospheric ³⁶Cl levels were increased significantly by nuclear testing during the 1950’s, i.e., the “bomb pulse” ³⁶Cl. Peak fallout of ³⁶Cl from thermonuclear devices in the western Pacific between 1952 and 1958 amounted to much more than 100 times the natural fallout and thus is a key tracer. The bulk of this bomb-pulse ³⁶Cl was washed out of the atmosphere by 1965.-

Systematic sampling (every 200 meters or 656 feet) and featured-based sampling (in or near faults or concentrated fractures) within the ESF for ³⁶Cl was and continues to be conducted. Analyses of several samples obtained near faults or concentrated fractures have revealed bomb-pulse levels of ³⁶Cl. The likely explanation for these high levels of ³⁶Cl is the presence of fast flow paths (less than 50 years) from the surface to the ESF. The discrete nature of the locations where the bomb-pulse signals were observed indicates the existence of isolated fast (fracture) paths through the geologic strata above the ESF. There is some correlation of fast-path locations with surface structural features (e.g., faults). The bomb-pulse signals of ³⁶Cl indicate only that some water has infiltrated from the surface and percolated to the ESF in less than 50 years. They give no indication of the amount of water flowing through fast paths.

An additional source of information is matrix ground water having ³⁶Cl levels higher than present-day values but lower than bomb-pulse levels. This matrix ground water is more widely distributed than the bomb-pulse ³⁶Cl, which is found only at isolated locations. Water containing intermediate levels of ³⁶Cl is thought to have an age of 10,000 to 30,000 years.¹¹ If 10,000 to 30,000 years were required for this water to travel from the surface to the ESF depth, modeling studies indicate that net infiltration rates during that time would have been in the range of 1 to 10 millimeters (0.04 to 0.4 inches) per year.¹²

Two distinct flow systems appear to exist in Yucca Mountain through which precipitation can move downward through the unsaturated zone to the water table. Bomb-pulse (high) levels of ³⁶Cl indicate that rapid flows of undetermined magnitude occurred through fractures in the last 50 years. Fracture flow is presumably episodic, occurring only after infrequent, intense precipitation events at the surface of Yucca Mountain. However, other data indicate that there also is a slower, but more or less continuous, flow through the rock matrix. Thus, there appear to be two systems of flow, some travel times being less than 50 years and others ranging upward to 10,000-30,000 years or more.

¹¹ Data from pack rat middens indicate that the atmospheric levels of ³⁶Cl in the past (10,000 to 30,000 years ago) were about twice as large as present-day values.

¹² Total precipitation at Yucca Mountain is about 150 to 170 mm per year. Most of this water runs off or returns to the atmosphere, but 1 to 10 mm/yr infiltrates and percolates into the mountain.

¹⁰ At some locations, there are more than 12 fractures per meter.

The spatial distribution of the bomb-pulse ^{36}Cl data provides information on the distribution of fast flow paths along the ESF. The data clearly indicate that the Paintbrush Tuff nonwelded unit, a geologic stratum located 200 meters (660 feet) above the proposed repository level and once thought to be essentially unfractured, would be a leaky “umbrella” over a repository. Accordingly, the conceptual model of flow in the unsaturated zone now includes occasional locations of fracture flow through the Paintbrush nonwelded unit.

Other studies — of calcite and opal deposits in fractures, including the uranium isotopes in those coatings — also suggest that the long-term average flow of water through the proposed repository level has been in the range of 1 to 10 mm/yr. This is more than 10 times as large as estimated one year ago. The implications of this greater flow estimate for repository design and the site-suitability decision may be substantial and have yet to be fully integrated. The Board also notes that infiltration estimates remain preliminary and approximate. Further changes are likely as more data are acquired.

Surface-Based Testing

The amount, distribution, and ages of water at and below the repository level may be the most important characteristic affecting the suitability of the Yucca Mountain site. Water can corrode waste packages, dissolve radioactive materials from the wastes, and carry them to the accessible environment. Many studies of Yucca Mountain are attempts to determine how precipitation at the surface of the mountain might penetrate to and beyond repository depth and affect repository performance.

Surface Infiltration and Percolation of Precipitation

Net infiltration at Yucca Mountain varies significantly with time and space. No single number can describe it over a wide region adequately for a long period of time. Data collected by the U.S. Geological Survey over the last 10 years indicate that the average net infiltration has been in the range of 5 to 10 mm/yr over Yucca Mountain and 3 mm/yr regionally.¹³ In some locations, net infiltration has

been significantly higher (~20-30 mm/yr),¹⁴ while in areas of deep alluvial (soil) cover, it is essentially zero.¹⁵ Net infiltration appears to be somewhat higher west of the ESF (where the waste would be emplaced) than to the east.

Data have been compiled to produce net infiltration maps and predictive net infiltration models for Yucca Mountain. Net infiltration can be predicted for each combination of controlling features, such as soil and bedrock properties, vegetation cover, and precipitation. This net infiltration model, in principle, could be coupled to large-scale climate modeling to simulate net infiltration rates for various future climate scenarios. The Yucca Mountain net infiltration model produces estimates of net infiltration (from soil-saturation measurements) that are consistent with those deduced from environmental isotope data (especially ^{36}Cl) and from measurements of temperature variations with depth.¹⁶

Pneumatic Testing

Considerable progress has been made in collecting and interpreting pneumatic data. Drill holes have been equipped with instruments by the U.S. Geological Survey, and separately by Nye County, to observe and analyze the attenuation and delay of atmospheric-pressure disturbances at depth¹⁷ (i.e., below the Paintbrush nonwelded unit). The pressure response at depth provides quantitative data on the vertical air permeability of the Paintbrush nonwelded unit. Although the data provide no direct information on water flow through the Paintbrush nonwelded unit, the data are important for describing vapor and gas flow and for calibrating the physical rock properties used in the hydro-

¹⁴ Ed Kwicklis, U.S. Geological Survey, arrived at a somewhat similar estimate of percolation at Pagany Wash on the basis that cooler water percolating downward would depress the local temperature. Using well-known relations and the measured temperature profiles, he estimated the local percolation flux to be in the range of 12 to 18 mm/yr.

¹⁵ The soil acts as a “sponge,” storing water until evaporation and transpiration of plants return most of the water to the atmosphere.

¹⁶ Temperatures in regions where cooler surface water is percolating downward are found to be depressed below the regional profile. Through a numerical analysis, the flux of water can be estimated from changes in the temperature-depth profile from its regional value.

¹⁷ Changes in atmospheric pressure at the surface of Yucca Mountain cause air to flow into or out of the mountain. The size and timing of pressure changes at depth, when compared with surface pressure changes, provide information about the “permeability” of the mountain to air.

¹³ The last 10 years have been a time of unusually high precipitation because of the El Niño effect.

logic model of the unsaturated zone. Because the Paintbrush nonwelded unit was thought to be unfractured, it was expected to be a good pneumatic barrier between the highly fractured geologic strata above and below it. However, pneumatic testing in the ESF tunnel indicates that the air permeability of the Paintbrush nonwelded unit is higher than the air permeability values measured on core samples, suggesting that there are faster paths for gas flow, and potentially water flow, through the Paintbrush nonwelded unit than seen in the borehole data.

Water Flow in the Saturated Zone

Radionuclides that eventually reach the saturated zone will be diluted by ground water as it moves toward the accessible environment. Processes such as molecular diffusion from fractures into the rock matrix, dispersion due to the heterogeneous nature of the geologic flow system, and sorption of radionuclides on mineral surfaces will contribute to the dilution and retardation of the radionuclides. Tracer testing at three wells, referred to as the "C-well complex," is designed to measure the nature of these processes over a selected depth interval in the saturated zone. Injecting multiple reactive and nonreactive tracers of significantly varying diffusion coefficients may help to separate and quantify the effects of the various processes. The magnitude of the dispersion and dilution processes remains one of the largest uncertainties about transport in the saturated zone.

The C-wells are in an easterly draining valley near Bow Ridge, approximately 1.5 miles east of the eastern edge of the potential repository within Yucca Mountain. Each well penetrates to approximately 900 meters (3,000 feet) below the surface, and the water table is 400 meters (1,300 feet) below the surface. The well separations are approximately 30, 68, and 77 meters (100, 225, and 250 feet). Flow in the saturated zone at the C-well complex occurs primarily in fractures. There is evidence that the flow in the saturated zone is stratified because of several low-conductivity zones. The tests isolate and focus on a particular conductive zone.

Testing with conservative tracers (tracers that do not sorb or react in any way with the rock surfaces) is expected to provide information on dispersion and matrix diffusion in the saturated zone. These phenomena determine, in part, the amount of dilution and dispersion of radionuclides that occurs during transport through the saturated zone to the accessible environment. Mixing also will be strongly in-

fluenced by the assumed characteristics of the well through which water would be pumped from the saturated zone. Because assumptions about mixing at a well may be so important, it is not clear that additional work in the saturated zone would provide significant quantitative resolution of the extent of dilution and dispersion in the saturated zone.

Corrosion Measurements

Laboratory testing is a necessary and important supplement to site-characterization activities at Yucca Mountain. Most of the laboratory testing takes place at the DOE's national laboratories,¹⁸ although a significant amount takes place at other laboratories as well. The advantages of laboratory testing include low cost and reproducibility. The disadvantage is that the testing takes place away from the site and at very small scale, requiring the results to be extrapolated to real-world conditions.

Much laboratory testing was deferred in the first nine months of 1996 because of inadequate funding. The Board is very pleased, however, that enough funding was found to complete construction of the long-term corrosion apparatus at Lawrence Livermore National Laboratory. The apparatus has been up and running since September 1996.

On the basis of current knowledge of Yucca Mountain, the Board believes that a robust engineered barrier system that ensures that waste packages will remain intact for thousands of years can be designed. However, demonstrating this possibility in a convincing fashion will require carefully controlled and long-term corrosion data taken under conditions that approximate the most rigorous conditions likely to be encountered in a repository. The tests now underway at Lawrence Livermore National Laboratory should be able to produce the required data.

At least three years of long-term corrosion research should be completed before site suitability is determined. The Board believes that up to 10 years of corrosion research will be necessary for supporting a licensing decision to permit repository operations.

¹⁸ Examples of testing activities at national laboratories include vitrified high-level-waste leaching at Argonne National Laboratory, adsorption and retardation testing of radioisotopes on tuff at Los Alamos, leaching of spent fuel at Pacific Northwest, and thermophysical rock properties at Sandia.

Conclusions and Recommendations

The conclusions and recommendations presented below are of a general, or overview, nature. More technically detailed conclusions and recommendations are presented in the following chapters.

Conclusions

1. The Board believes that the DOE has substantially improved its understanding of the complexities of the site. Recognition of increased net infiltration rates (and their spatial variability) illustrates the need for a thorough exploration and testing of the repository level, including evaluation of ambient moisture conditions in a sealed-off alcove or portion of tunnel, especially in the area west of the ESF where wastes would be emplaced.

2. The Board calls attention to the significance of the termination of the MPC development effort. The concept had great potential to improve the safety and efficiency of the overall system for management and disposal of spent fuel. If the private sector is to provide the waste packages, the specifications should include uniformity of canisters and minimum need for transfers of spent fuel among canisters.

Recommendations

1. A decision to locate the nation's primary centralized storage facility for spent fuel at or near Yucca Mountain should be deferred until the suitability of the site as a repository location has been determined.

2. To the extent possible under the market-driven initiative, efforts to develop storage and transportation casks should retain the advantages (e.g., standardization) previously offered by the MPC concept.

Chapter 2

Hydrology, Radionuclide Transport, and Performance Assessment

Until recently, the proposed repository area within Yucca Mountain was thought to be very dry. The amount of water that could contact the waste was assumed to be very small, and the travel time for released radionuclides to reach the water table and move on to the accessible environment was thought to be very long. These favorable attributes of the natural barriers were expected to supplement long-term waste containment by the waste packages and help provide “defense-in-depth” for long-term waste isolation at Yucca Mountain. Now, it appears that more water may percolate through the mountain than previously expected. This chapter analyzes issues related to the hydrology of Yucca Mountain and potential transport of radionuclides from a repository. Then, the chapter reviews issues in performance assessment, the tool that will play a major role in evaluating the suitability of the site.

Hydrology and Radionuclide Transport

Data from site characterization are showing that the fractured tuffs, and the unsaturated zone at Yucca Mountain as a whole, are more complex and difficult to characterize than originally envisioned. The primary reason is the distribution of fast, but episodic, flow paths through fractures and voids. In addition, the evidence indicates that a larger amount of water is percolating deep into the mountain than anticipated earlier. The existence of rapid-flow phenomena has been indicated by the measurement of 50-year-old bomb-pulse ^{36}Cl levels at discrete locations in the ESF. These and other data indicate the existence of both fast and slow water movement from the surface to the ESF. The fast-path data do not indicate the amount of flow or its significance in repository performance. Characterizing and realistically modeling these phenomena remains an important objective of the project.

Resolving questions about the hydrology of the Yucca Mountain unsaturated zone is fundamental in a site-suitability determination. The amount and geochemistry of the water that may reach waste packages in the proposed repository, corrode them, and carry radionuclides to the water table where they can move to the accessible envi-

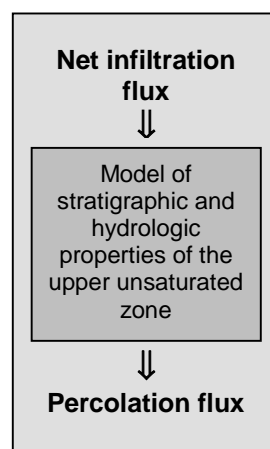
ronment are key scientific issues in isolating radioactive waste. The following sections discuss the progress that has been made on these key issues and what remains to be done.

Unsaturated Zone

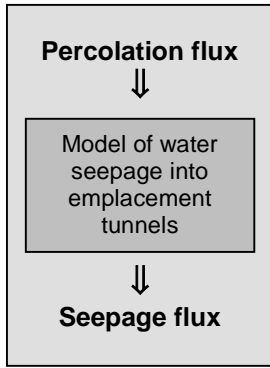
Over thousands of years, waste packages are expected to degrade, permitting a slow release of radionuclides from the engineered barriers to the host rock. Then, water percolating through the unsaturated zone can carry radionuclides to the underlying saturated zone and on to the accessible environment. There are two key issues for evaluating the performance of the natural barriers: the time required for the radionuclides to migrate to the accessible environment and the amount of dilution that will occur.

Hydrology of the Unsaturated Zone

The key objectives of the unsaturated zone studies are to (1) determine the magnitude and distribution of the percolation flux at repository depth, (2) estimate the fraction of percolating water that will enter the emplacement tunnels, (3) estimate the fraction of water entering the emplacement tunnels that will contact the waste packages to corrode them and subsequently mobilize and transport the waste, and (4) predict how effectively the water will transport the radionuclides to the saturated zone.

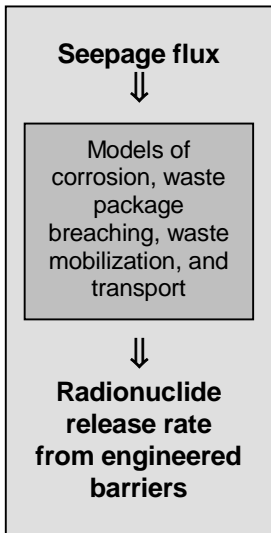


The percolation flux at repository depth is the single most important input for modeling radionuclide releases from the engineered barriers and transport to the saturated zone. During the last year, there has been a significant advance in understanding how precipitation at the surface infiltrates into the mountain and how the portion not lost to evapotranspiration eventually migrates, or “percolates,” down to repository depth.



The next major uncertainty is estimating the fraction of percolating water that will drip into the emplacement tunnels — the seepage flux — a portion of which may contact the waste packages. The seepage flux is bounded by the percolation flux and, in all probability, is much smaller because capillary forces tend to move water around the tunnel surface.

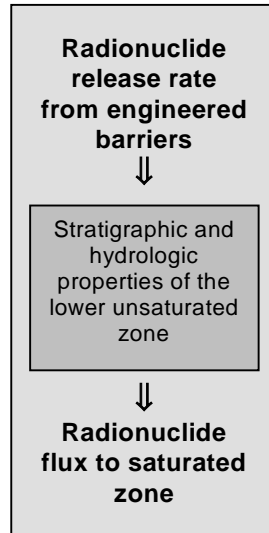
However, there is a large uncertainty about the precise fraction. Still to be determined is whether the tunnels and waste packages can be located to minimize seepage and its effect and whether additional engineered barriers are needed, such as backfill or drip shields, to ensure adequate performance.



The seepage flux, in conjunction with models of waste package deg-radation, waste mobilization, and transport out of the engineered barriers, will yield an estimate of the rate of release of radionuclides to the host rock. Bounding the release rate, especially in response to climate changes, will be important in making decisions about the need (if any) for additional engineered barriers.

Modeling of Transport in the Unsaturated Zone

Radionuclides released from the engineered barriers will be sorbed and diluted during transport to the environment. The important characteristic of the unsaturated zone is that, except for a component of faster transport through fractures, the average travel time to the saturated zone is very long (more than 10,000 years). If the fraction of radionuclides transported through fractures is very small, then the unsaturated zone below the repository will be an additional barrier. This will provide valuable redundancy to protect against unanticipated early release and transport from the waste packages to the saturated zone. Thus, bounding the transport that occurs through fractures is a major goal of modeling the unsaturated zone.



During 1996, progress was made in developing the models of transport to the accessible environment. Several key advances in data collection and in modeling are important contributions to the design and performance evaluations of the repository:

- The discrete locations in the ESF of bomb-pulse ³⁶Cl indicate the existence of isolated, faster (less than 50 years) paths through fractures or other openings in the Paintbrush nonwelded unit to the repository level. If similar features also exist beneath the repository,

modeling indicates that radionuclides may move rapidly downward through the fracture system, resulting in a high peak dose. It is not necessary for most of the radionuclides to travel through the fractures; on the contrary, a typical split in simulations is 90 percent matrix and only 10 percent fractures. However, 10 percent is often enough, when coupled with shorter travel times and less attenuation of radionuclides, to result in a peak dose controlled by the fracture transport. *It should be emphasized that at present no data allow determining what fraction of flow would occur through fractures if a repository were built at Yucca Mountain.*

- The sorption of long-lived radionuclides on mineral surfaces (i.e., their retardation) may have little effect on projected long-term radiation doses to individuals if the release of radionuclides from engineered barriers is slow and continuous.

Saturated Zone

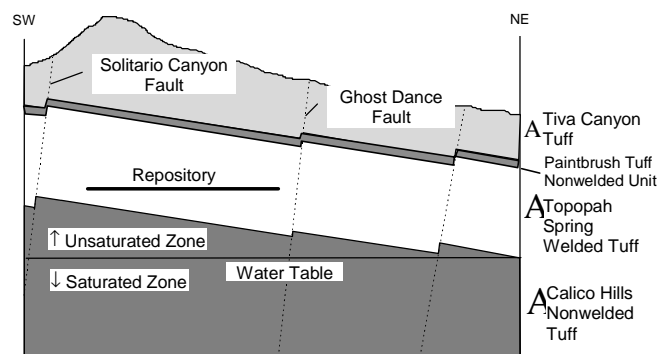
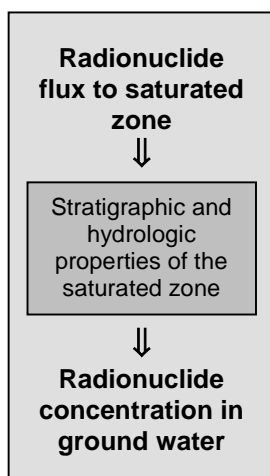
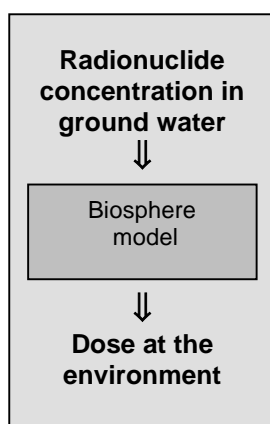


Figure 4. Schematic of Unsaturated Zone, Saturated Zone, and Repository



The saturated zone lies at the water table an average of approximately 500 meters (1,600 feet) below the surface at the Yucca Mountain site. Flow in the saturated zone is generally southwesterly toward Amargosa Valley, approximately 30 km away. The source of the water for the saturated zone is primarily in the higher elevations to the northeast, where precipitation is significantly greater and temperatures somewhat lower. The flux of water in the saturated zone averages about 1 to 2 meters/yr (3.3 to 6.6 feet/yr) but is highly variable with depth. The flow is much greater than the recharge (net infiltration) of 1 to 10 mm/yr (0.04 to 0.4 inches/yr) from the footprint of the repository. Figure 4 shows schematically the relative locations of the water table beneath Yucca Mountain, the unsaturated and saturated zones above and below the water table, and the proposed repository location.

The concentrations of radionuclides entering the saturated zone from above will be reduced by various processes during their transport to the accessible environment. Because of the greater volume of flow in the saturated than the unsaturated zone and the heterogeneous nature of the flow system, the radionuclides will be mixed and dispersed, decreasing their concentrations. Practical and direct measurement of these processes at the required length scale is not possible. Thus, to a great extent, the project must rely on mathematical models and small-scale measurements for predicting radionuclide concentrations and potential doses.



A further complexity is that the assumed depth of mixing within the saturated zone and the biosphere model of the location and amount of water withdrawn by an individual or a population could have a significant effect on the estimate of doses. Overly conservative assumptions could make achieving compliance with the repository's safety

standards very difficult and expensive. For this reason, a timely promulgation by the EPA of the specifications of the standard, including assumptions about the biosphere model, would be beneficial for the project.

Although all of the models are still preliminary and presumably will be made more realistic for analyses supporting the VA, they are an improvement over the models used in previous performance assessments. Several specific results and observations are as follow.

• Dispersion in ground water, caused by the heterogeneity of the saturated-zone flow system, is very difficult to model accurately because of the practical problems of acquiring data over long distances and times. The C-well tracer studies will help to provide some data, but the data will be at a single location and at a comparatively short length scale. Thus, they may not be representative of the entire saturated zone.

- A longer distance to the accessible environment is clearly beneficial for meeting a dose standard within a regulatory time period. However, if there is no regulatory cut-off time, a longer transport path may not materially alter a licensing decision. Projected doses at 25 km, as compared with 5 km, differ by a factor of about 5, all other factors being held constant. Dose estimates appear to be conservative because, in the real system, dilution may be greater. However, there are no data to support a realistic estimate of dilution.

An important decision concerning the saturated zone is how much the uncertainty in repository performance can be reduced through further characterization and testing. From the recent modeling of transport in the saturated zone, the uncertainties in the computations due to data uncertainties appear to fall within about a factor of 10. Also not clear is whether further characterization can provide the data for reducing the uncertainty. Other subsystems of a performance assessment have a much greater uncertainty and have a higher probability of being resolved through further testing and exploration. Thus, further studies of the saturated zone beyond those now planned or under way — completion of the regional flow model, the C-well testing, and the proposed conceptual modeling of transport to account for dispersion and dilution — may not be cost-effective.

Peer Review of the DOE's Thermohydrological Processes Research

During August 21-24, 1995, a peer review team was convened by the Yucca Mountain Site Characterization Office to conduct an external review of the thermohydrological modeling and testing activities at Yucca Mountain.¹⁹ This effort by the DOE was in part a response to the need for reviewing priorities for activities at Yucca Mountain because of a severely declining budget for fiscal year 1996. Priorities were to be based on the waste isolation strategy being developed by the M&O contractor at that time.

In its summary report (Witherspoon 1996), the peer review team identified a set of critical technical issues that must be resolved by the testing and modeling work at Yucca Mountain. The team also presented an assessment of the adequacy of the field and laboratory testing program, discussed the modeling program, and presented 23 recommendations for the modeling and testing programs for the DOE's consideration.

Despite the review's cost and demands placed on the project personnel's time and resources, it achieved its stated objectives. The review was beneficial to the project and provided an assessment that is independent of the project and its oversight bodies. There were no major surprises or controversies, and there was reasonable unanimity on the critical issues related to repository performance. The Board believes that such independent reviews of the critical issues faced by the project are essential in developing consensus and in setting priorities for use of the project's resources.

Need for an East-West Crossing

The DOE *Program Plan* now calls for the completion of the ESF, including two exploratory alcoves eastward across the Ghost Dance Fault, by the end of fiscal year 1997. An east-west crossing of the potential repository block, to the west of the existing ESF, is planned for the 1998-1999 time period only *if deemed necessary* (DOE 1996a).

The current exploratory tunnel is located at the same level and close to, but not in, the proposed repository area. While

important data are being obtained from the tunnel, direct observation of the repository block is necessary to address remaining uncertainties about water movement and faulting, and to help in determining the most appropriate design and operational strategy for the proposed repository. In the Board's view, the best way to obtain the data needed is to construct a 1,200 meter (4,000 foot) long tunnel, 3-5 meters (10-16 feet) in diameter, starting at the current main tunnel and extending west directly into and across the proposed waste emplacement area. Constructing this east-west crossing conforms to standard engineering practice — you should not decide to embark on a major underground project without seeing firsthand what the relevant geology is like.

There are four reasons why an east-west tunnel is, in the Board's view, essential for a site-suitability determination.

- First, there has been no underground exploration, and very little surface-based testing, in the proposed waste emplacement area, which is west of the ESF.
- Second, the properties of the rocks at Yucca Mountain are highly variable, both across the site and with depth. It is difficult to use the geologic conditions found in the ESF to accurately predict the properties of the proposed waste emplacement area.
- Third, surface studies suggest that water may infiltrate in areas on the west side of the emplacement area at rates 2 to 3 times higher than on the east. If seepage at the proposed repository level is also higher, the increased moisture could affect repository and waste package design, cost estimates, and isolation of wastes from the accessible environment.
- Finally, at Yucca Mountain the important faults and fractures follow a north-south trend and are nearly vertical, making them difficult to evaluate with vertical boreholes drilled from the surface. The nature of the faults and fractures will affect repository excavation, selection of ground support, and the cost of repository construction.²⁰

¹⁹ Dr. Paul Witherspoon (Lawrence Berkeley Laboratory) chaired the peer review team. The other members were: Dr. Allan Freeze (U. of British Columbia), Dr. Francis Kulacki (U. of Minnesota), Dr. Joseph Moore (U. of Utah), Dr. Franklin Schwartz (Ohio State U.), and Dr. Yanis Yortsis (U. of Southern California).

²⁰ In addition, the Board notes that an east-west tunnel could possibly aid in understanding earthquake faulting, particularly near the Solitario Canyon Fault.

Performance Assessment

The TSPA is the principal method of evaluating the ability of the proposed repository (both engineered and natural components) to contain and isolate waste. There have been three major iterations of performance assessments (e.g., Sandia 1992, Sandia 1994, and TRW 1995a) carried out by DOE contractors for the Yucca Mountain site. The Board has discussed the general aspects of the TSPA and the specific individual studies in previous Board reports (NWTRB 1990 and subsequent reports). Although the TSPA has not always been used as such, its primary role has been to help guide site-assessment data requirements, set priorities, and evaluate different engineering designs. Insights are developed primarily through a *relative comparison* of the level and uncertainty of the calculated health risk to humans associated with each option or assumption. In past TSPAs, the DOE correctly pointed out the tentative nature of the specific values of calculated risks and conclusions that may be reached about the overall safety, or lack of safety, of the proposed repository. Now that better models and more advanced repository design information are in hand, the DOE is undertaking a new iteration of a TSPA that will play a different and clearly more prominent role than in the past.

TSPA in a New Role

The next iteration of a TSPA has been called the “TSPA-viability assessment” (TSPA-VA).²¹ According to the DOE, the TSPA-VA will be available by September 30, 1998, and will describe the “probable behavior of the repository in the Yucca Mountain geological setting relative to the overall system performance standards.” (DOE 1996d). The DOE’s intention is for the TSPA-VA, its revisions, or successive iterations to play dominant roles in assessing compliance with the DOE’s revised siting guidelines in 10 CFR Part 960 (currently scheduled for June 1999),²² recommending the site to the President (currently scheduled for 2001), and applying to the NRC for a license to construct the repository (currently scheduled for March 2002).

All these applications necessitate assessing compliance (directly or indirectly) with respect to an EPA-promulgated

standard. This increases the importance of the *absolute* level of the calculated risks, placing additional burdens on the TSPA and requiring answers to two general questions:

1. Does the TSPA demonstrate the safety of the repository? This fundamental question is made particularly difficult because there is not yet an accepted standard for measuring the safety of long-term repository disposal.²³ Demonstration of safety may mean different things to different audiences. Regulatory agencies, such as the NRC, usually emphasize demonstrating compliance with a standard or a set of standards using specific criteria laid out in regulations. The general scientific and technical community usually will not limit itself to those criteria but will tend to look at the validity of all the scientific and engineering assumptions.²⁴ Nontechnical decision-makers, such as elected or appointed officials, may be concerned about the political implications of a safety analysis. A skeptical public could very well judge the analysis not so much on its technical merit but on the sponsoring agency’s reputation for honesty and openness.

2. Does the TSPA generate confidence? The “robustness” of the TSPA, that is, its ability to withstand the challenges brought about by new knowledge and changing assumptions, will be a prime factor in generating and maintaining confidence in its conclusions. Confidence also will be greatly enhanced by the extent to which those viewing the analysis can understand it. A conclusion based on unclear assumptions and opaque models will be suspect.

What Are the Desirable Characteristics of a TSPA?

In the Board’s view, the likelihood of obtaining positive answers to the two questions stated above will be greatly enhanced if the TSPA-VA and its derivatives or successors possess the following characteristics.

1. *Transparency.* Transparency is the ease of understanding the process by which a study was carried out, which assumptions are driving the results, how they were arrived at, and the rigor of the analyses leading to the results. Transparency is difficult to achieve when dealing with complex models and submodels with many interactions. Transpar-

²¹ Chapter 1 of this report contains a discussion of the VA.

²² As discussed in Chapter 1, the DOE’s proposed revision to its siting guidelines would replace a long list of individual technical criteria with a single performance objective for the overall repository system. Compliance with the performance objective would be evaluated by means of a TSPA.

²³ Chapter 4 of this report summarizes the status of efforts to develop standards for a Yucca Mountain repository.

²⁴ For example, some scientists might not be satisfied with criteria narrowly specifying the biosphere thousands of years in the future, and some engineers could take exception to a rule stipulating that drilling technology in the future will be the same as today.

ency is important because models are only abstractions or approximations of reality. Understanding them is a necessary component of establishing confidence that they are correct. Only if the abstractions are clearly visible and fully understood can observers develop a sense of confidence that the models are reasonable approximations of reality.

Understanding what drives a TSPA is akin to peeling an onion layer by layer, except that in a TSPA, each additional layer can provide markedly different insights into how the overall system functions. In TSPA-95 (TRW 1995a), for example, details about water drainage at the repository level and the proportion of fracture flow going into a tunnel had a great effect on the number of waste packages subject to corrosion and, ultimately, on repository performance.

Achieving transparency also requires different levels of explanations for different audiences. The hydrologist or engineer may need detailed knowledge of a specific model and its assumptions, but a nontechnical decision-maker or a member of the public will want a simpler, more fundamental and conceptual explanation that conveys what a model does, why that is important, and interprets the results of analyses. Transparency also can be increased by well-chosen sensitivity studies that show the effect of different assumptions and models. The DOE has made progress in this area, as evidenced by TSPA-95. One example of the kind of sensitivity study that both the technical specialist and the nontechnical generalist would find helpful is the effect of future climate change and increased precipitation on risk to the public from a repository at Yucca Mountain.

2. *Proper treatment of uncertainty.* This area is of particular concern to decision-makers and to technical specialists who are familiar with the difficulties involved in modeling heterogeneous geology and the behavior of natural and engineered systems over thousands or tens of thousands of years. Examples of uncertainties include how long the outer layer of the waste container will provide cathodic protection²⁵ to its inner layer and the amount and distribution of water infiltrating into the mountain and

working its way down to the repository into the emplacement tunnels. This latter example illustrates the different kinds of uncertainty. There is the modeling uncertainty associated with the model itself, an example being the nature of matrix and fracture-flow interaction in unsaturated rocks; the parametric (data) uncertainty associated with defining parameters, such as porosity, permeability, and fracture density, needed to use a given flow model; and the stochastic uncertainty, or randomness, inherent in natural processes and in the fine-scale spatial distribution of rock properties.

Keeping track of multiple uncertainties of different kinds is a formidable task for large and complex calculations such as those in a TSPA. On one hand, simple errors or uncertainties that are not addressed appropriately can propagate through an analysis and affect the bottom-line result or the conclusions. On the other hand, dealing with so many different uncertainties can sometimes lead to double counting, making the cumulative uncertainty larger than warranted. In that case, mean-based measures, which are highly dependent on uncertainty distributions, can lead to unnecessarily high estimates of risk.

Uncertainties can be dealt with in several ways. Sensitivity studies, which show the effect of higher and lower values of a variable, can help show the significance of uncertainties. Conservative or bounding assumptions can be used. An example of this in TSPA-95 is the assumption that the zircaloy cladding surrounding the spent-fuel pellets has no delaying effect on the release of radionuclides from a corroded waste package. In reality, the cladding may substantially delay releases. If conservative assumptions have a marked effect on results or conclusions about safety, uncertainties may have to be addressed directly. This can be accomplished either through collecting new data or, if this is not possible or does not help, using a defensible uncertainty distribution as input to the TSPA. When the data do not permit an unambiguous definition of the uncertainty, careful elicitation of expert judgment can be very useful. This was the course taken for volcanic hazard, as described below.

3. *Establishing validity using analogues and simplified calculations.* Validity²⁶ is an all-embracing characteristic that is of great importance to technical and nontechnical

²⁵ Cathodic protection occurs when the two different metals used for the layers of a waste container are in contact in the presence of an electrolyte (water with dissolved salts). The more easily corroded outer layer corrodes first, inhibiting corrosion of the inner layer.

²⁶ A model is considered "valid" if it provides a reasonably accurate representation of reality. The required degree of accuracy will, of course, depend on the specific application of a model (e.g., supporting a repository licensing decision).

audiences alike. In many circumstances, the need to establish validity is related to the existence of uncertainty, as discussed above. The best way to assure skeptical audiences of the validity of a complicated calculation is to have independent confirmation that the conclusions are correct. The most likely candidates in this case would be natural and engineering analogues. In Sweden, for example, a copper canister's resistance to corrosion in a reducing environment is affirmed through the study of copper electrodes that have been implanted in the ground for about 100 years, historic and prehistoric copper and bronze artifacts up to 5,000 years old, and naturally occurring native copper ore deposits that are millions of years old.²⁷

The United States has been involved in joint international studies of ancient uranium deposits in Africa, Canada, Australia, and Latin America whose primary purpose was to gain useful information about the natural migration of radionuclides. The DOE's involvement in these studies has greatly diminished because of lack of funds and concerns about the complexity of applying information from different and relatively unknown natural conditions to Yucca Mountain. Recently, interest has increased in a uranium ore deposit in unsaturated volcanic rocks in Mexico.

Another approach to supporting the validity of a TSPA is to perform simple calculations that capture some of the main elements of the complex natural and engineering system being modeled.²⁸ Thus, for example, we may assume that long-term repository performance can be broken down into six major components: (1) the amount of water entering the emplacement tunnels, (2) the durability of the waste packages, (3) the rate at which degraded waste packages (and the entire engineered barrier system) release radionuclides, (4) the rate at which the radionuclides are transported to the saturated zone, (5) the dilution potential of the saturated zone, and (6) the rate and total uptake of radionuclide-containing water by an exposed member of the public.

The text box on the following page displays a simple calculation that shows the significance of radionuclide solu-

bility and its relation to the flow of water in determining the release rate of the important radionuclide, neptunium, from the repository's engineered barrier system. Performing such simple calculations can help determine what combination of essential attributes would result in acceptably low consequences to the public. If there is reasonable assurance that this combination or some other suitable combination of attributes is present, then we have gained additional confidence that the repository will perform as expected.

Simple calculations cannot capture all complex interactions that may be important. As a result, they cannot be a substitute for a complete performance assessment. They can, however, clearly convey how and to what extent major components of the repository system contribute to safety. Simple calculations also allow easier scrutiny of the assumptions and judgments on which an analysis is based.

4. *Validity using outside expertise.* On numerous occasions, the Board has pointed out the importance of the increased use of outside expertise by the DOE in the Yucca Mountain program. The use of outside expertise not only ensures consideration of views that are not necessarily found within the DOE and among its contractors, but it also increases the program's technical credibility. This is true for both internal programmatic studies, such as how to configure the ESF, and for the studies, such as TSPAs, that will be evaluated by a wide range of regulatory, technical, and nontechnical audiences.

Typically, outside expertise is used in the form of a peer review. The DOE plans to convene a peer review panel²⁹ that will develop interim evaluations of the TSPA-VA at different phases in its development, and conduct a comprehensive review of the final TSPA-VA, including recommendations for conducting the TSPA for the license application. Such a review has been termed a "participatory review." Its advantage is that it allows midcourse corrections for preventing serious problems that otherwise might not be identified until after the TSPA is completed. The disadvantage is that the peer reviewers might be perceived to lose their objectivity as they interact with the project over time. The alternative, a "late-stage review," that is conducted after a project is completed may be more credible but less useful. The two types of reviews were dis-

²⁷ Copper is thermodynamically stable in the reducing environment found at repository depth beneath the sites being considered in Sweden. This would not be true in the oxidizing environment at repository depth beneath Yucca Mountain.

²⁸ This approach also was recommended by the National Research Council's Committee on the Waste Isolation Pilot Plant in its review of that project (NAS/NRC 1996b).

²⁹ The first meeting of the panel occurred on February 10-11, 1997.

SIMPLIFIED CALCULATION: SOLUBILITY, WATER FLUX, AND RELEASE RATE

Recent performance assessments of the proposed Yucca Mountain repository indicate that the largest long-term contributor to individual dose is neptunium, specifically, ^{237}Np . The dose from this radionuclide is largest more than 100,000 years after the waste is first placed in the repository. By then, the waste package likely will have lost its ability to keep downward percolating ground water from contacting the waste, mobilizing it, and transporting harmful radionuclides to the accessible environment. The purpose of the following calculation is to emphasize the important role of neptunium solubility in this process.

After 1,000 years, each of the estimated 10,000 waste packages will contain approximately 70 moles of ^{237}Np (one mole equals 237 grams). This amount includes both the neptunium originally in the spent fuel when it was brought to the repository and the additional amount generated by the radioactive decay of other radionuclides. Presently, NRC criteria (10 CFR Part 60) limit the annual release rate of radionuclides from the repository's engineered barriers to 1/100,000 of each radionuclide's inventory at 1,000 years after permanent closure. This means that the average release rate of ^{237}Np per package should be no more than 0.0007 moles per year. Investigations indicate that the solubility of ^{237}Np is less than 10^{-3} moles per liter of water. If we assume 10^{-3} as an upper solubility bound, 0.7 liter of ground water coming in contact with the waste over the course of the year could be sufficient to dissolve the annual limit of neptunium.

How much water is actually available? According to the latest DOE estimate, the average annual percolation flux at the repository horizon is about 5mm/yr. If the area of rock drained by each package is about twice its 5-meter length times the 5-meter width of the emplacement drift, 250 liters of ground water would be available. The needed 0.7 liter represents only about 0.25 percent of that water. In other words, under these assumptions, it would take only a very small portion of the water percolating down into the repository horizon to cause an "unacceptable" release. What factors could significantly change this? It does not seem very likely that the average percolation flux could change by an order of magnitude in either direction. The potential drainage area could increase by an order of magnitude if we assume that the potential drainage area for each package is 1/10,000 — there will be about 10,000 waste packages in the repository — of the 5-square kilometer repository area. The largest factor affecting this calculation is the solubility of ^{237}Np . The DOE indicates that the solubility could be two orders of magnitude lower than the upper bound, and one estimate (Langmuir 1997) places it as much as four orders of magnitude lower. If the solubility of neptunium is indeed this low, 7,000 liters of water per year would need to contact the waste in order to reach the release limit. This is more than would be available under the most adverse drainage conditions.

The question that hasn't been addressed is what fraction of the percolating water enters the drift, reaches the corroded waste packages, and dissolves and transports radionuclides. This depends very much on the fraction of percolating water in the fractures and the number of fractures entering each drift in the vicinity of the waste packages. This is a major focus of the hydrologic research at Yucca Mountain and, as shown above, its significance can be greatly affected by assumptions about radionuclide solubility, which is not clearly established for Yucca Mountain conditions.

cussed in a report (LLNL 1995) prepared by the Senior Seismic Hazard Analysis Committee, created and jointly sponsored by the NRC, the DOE, and the Electric Power Research Institute. The Board concurs with the National Research Council's review of that report (NAS/NRC 1996c), which states that in a participatory review, "Safe-guards must be established to preserve the objectivity of the review process."

In recent years, eliciting expert judgment for analytical studies has become more common. In fact, the purpose of the Senior Seismic Hazard Analysis Committee's report was to provide guidelines for the increased use of formally elicited expert judgment in estimating seismic hazards at nuclear power plants. The NRC has now issued informa-

tive and useful guidelines for using expert judgment to support repository development (NRC 1996).

Several groups formally elicited expert judgment on issues related to the high-level-waste program. The Electric Power Research Institute and the NRC-sponsored Center for Nuclear Waste Regulatory Analyses conducted demonstration studies on the hazard of earthquake-fault rupture at Yucca Mountain and the future climate in the Yucca Mountain vicinity, respectively. The most important study thus far is the probabilistic volcanic hazard analysis (PVHA) at Yucca Mountain conducted for the DOE (Geomatrix 1996). In the Board's view, the PVHA represents a successful application of elicited expert judgment. A credible process was used to arrive at a credible conclusion (see the text box on the next page).

PROBABILISTIC VOLCANIC HAZARD ANALYSIS FOR YUCCA MOUNTAIN

Volcanic hazard analysis for the proposed repository has been one of the most contentious issues about the Yucca Mountain site. Yucca Mountain rock was formed by volcanic ash laid down more than 10 million years ago. Although large-scale volcanic activity in the area has ceased, there has been some small-scale activity, particularly west of the mountain in Crater Flat. A few small volcanic cones and lava flows have periodically made their way to the surface of Crater Flat during the last few million years. The most recent volcanic activity occurred just south of Crater Flat at the Lathrop Wells volcanic cone. The timing and nature of the volcanic activity at the cone, some 15 kilometers from the proposed repository, have been the source of great contention between DOE-sponsored scientists at Los Alamos National Laboratory and individual scientists within the U.S. Geological Survey not currently working for the DOE. There also were strong differences of opinion among the Los Alamos scientists, those at the University of Nevada at Las Vegas, and those at the NRC-sponsored Center of Nuclear Waste Regulatory Analyses on issues related to the configuration of zones of volcanic activity and the methodology used for computing the hazard. The Los Alamos scientists maintained that most of these differences of opinion had little effect on the hazard — the probability that a volcanic event will intrude into the proposed repository — which they calculated as being about 2×10^{-8} per year.

The DOE commissioned a formal study for independently calculating the hazard. Its contractors convened a panel of 10 experts, all but one of whom were from outside of the Yucca Mountain Project. In the Board's judgment, the study was carried out in a highly professional manner. At the January 1996 Board meeting, one of the experts described the rigorous nature of the elicitation and the remarkable way in which the process was handled. After several workshops and field trips, the experts' views were elicited and the hazard was calculated. The experts were very selective in choosing which hypothesis to support and which not to support. Although several of the Los Alamos concepts received little weight, the group's estimated mean hazard was still about 2×10^{-8} per year, the same as the Los Alamos estimate.

A DOE-sponsored expert elicitation is under way for earthquake issues. The probabilistic seismic hazard analysis (PSHA) will develop estimates of vibratory ground motion and fault displacement for use in the design of the repository to be used in a TSPA and in the decision on the site's suitability. This elicitation is a large-scale study involving many experts and workshops. The first of a possible series of smaller-scale expert elicitations for the TSPA-VA also has been initiated. The purpose of this initial study is to characterize the spatial and temporal distribution of percolation flux at repository depth and seepage flux into the drifts. These are very important topics and, if successful, this elicitation will lead to others on topics related to hydrology and waste package performance. The DOE should be careful, however, not to allow budget and scheduling constraints to force the use of expert judgment as a substitute for scientific information that is reasonably obtainable.

5. *Public acceptance.* Although there is no formal requirement that the public accept the TSPA, to proceed without acknowledging the importance of encouraging public participation is condescending at best and a prescription for failure at worst. The likelihood of acceptance of a TSPA by the interested public will be greatly enhanced by the transparency of the TSPA, as defined above. If the perception is that the TSPA is like a large black box whose re-

sults can be dictated by some manipulator arbitrarily adjusting hidden knobs, public acceptance will not be attainable no matter how good the underlying rationale.

The more direct way to increase acceptance by the interested public is increasing their involvement. A recent report issued by the National Research Council (NAS/NRC 1996a) called for abandoning old concepts of characterizing risk that view risk characterization as a scientific and analytical process with little or no input from interested parties. Contact with the interested parties was assumed to be part of risk communication — that is, explaining the results of a completed analysis. As part of a new approach, the report argues for a process of *learning and feedback* among analysts, public officials, and interested and affected parties. Ideally, the interactions will help define the problem, the process by which it will be addressed, the information needed, the synthesis, and its evaluation. This kind of meaningful, early, and continuing participation can help prevent some of the problems that have resulted in the failure of past risk analyses to meet expectations.

Applying this approach to the Yucca Mountain TSPA would pose challenges to all parties: the DOE, the NRC, national and local public officials, and the interested public. There are no simple or guaranteed ways of increasing public acceptance of an analysis for a project as technically com-

plex and controversial as building a high-level waste repository. However, the Board firmly believes that a well-thought-out effort in this area, even at this late date, will have beneficial effects on convincing a skeptical public, or at least on making their criticism based on better information.

Conclusions and Recommendations

Conclusions

1. Additional data are needed from within the proposed repository location at Yucca Mountain on (1) structural features, (2) net infiltration, and (3) distribution of fast-flow paths. Without this information, technically supporting an evaluation of the suitability of the site to host a repository of adequate size will be difficult. The Board's view is that an east-west tunnel is the surest way to obtain the needed information.

2. The TSPA is entering a new and more demanding phase in the Yucca Mountain program. The TSPA-VA and its successors will be much more concerned with compliance and the levels of the calculated risk than previous efforts have been. The TSPA will be the primary mechanism for establishing the safety of the proposed repository, so establishing public confidence in the models' validity will be of great importance. The chances of meeting this goal can be greatly enhanced if the TSPA is transparent, pays proper attention to uncertainties, is coordinated with a waste isolation strategy, and finds ways, such as using natural and engineering analogues, simplified calculations, peer review, and outside expertise, to demonstrate its validity.

3. Although public acceptance of the TSPA is not formally required, it may be necessary to ensure that the interested public has opportunities to stay involved in the processes leading up to the decisions.

Recommendations

1. Before making a determination of the suitability of the Yucca Mountain site for a repository, the DOE should complete additional studies of the area west of the current exploratory studies facility, where wastes would be emplaced, to determine its geologic, hydrologic, and geochemical properties. The best way to obtain the needed information is excavation of a tunnel westward across the proposed repository block.

2. The DOE should make a concerted effort to ensure that future TSPAs are transparent and valid, that uncertainty is treated properly, and that any peer review of performance assessment or elicitation of expert judgment is objective.

3. The DOE should consider ways of increasing public understanding and acceptance of TSPAs. One possibility is to establish processes, modeled on the lines suggested in a recent report by the congressionally chartered Commission on Risk Assessment and Risk Management, for involving and engaging the public.

Chapter 3

Design

As discussed in Chapter 1, the DOE plans to produce a VA by September 30, 1998. One component of the VA is a design for the critical underground features of the repository. Each of the other components of the VA depends on the repository design to a degree.

In March 1996, the DOE published a four-volume document, *Mined Geologic Disposal System Advanced Conceptual Design Report* (TRW 1996a). The report presents a preliminary conceptual design of the proposed repository surface facilities, underground facilities, and waste packages. It also includes an estimate of the repository's total system life-cycle cost. This document is generally referred to as the "advanced conceptual design" (ACD). The ACD will continue to evolve as more information is developed about a potential repository at Yucca Mountain.

Since March 1996, the underground part of the repository ACD has evolved dramatically because of improved management, acknowledgment of the need for a credible repository design by 1998, and the input from a four-person board of consultants who have extensive experience and expertise in construction of major underground facilities.³⁰ The board of consultants emphasized the need to develop a construction and operational strategy in conjunction with the development of a conceptual design for the underground part of the repository. Approximately 75 percent of a repository's cost will be operation and maintenance over the life of the system (TRW 1996a, vol. 4) and therefore should have an early influence on the design. It is also possible that construction costs can be reduced if the design is developed with an understanding of how the repository will be operated.

The current ACD was developed for a "dry" mountain, that is, for the very low percolation previously assumed to be present at depth in Yucca Mountain. Now that percolation

³⁰ J. Lemley, large-system manager, CEO for design and construction of the English Channel tunnel; B. Bartholomew, construction planner and manager; R. Heuer, geotechnical engineer; L. Snyder, underground construction equipment designer. This is the same board of consultants established in 1995 to review construction of the ESF. Its charter has evolved to include advice on the design of a repository facility.

appears to be as much as 10 times greater than previously thought, many aspects of the design may have to be reconsidered. Until hydrologic conditions are established more conclusively, a more conservative design that makes greater use of engineered barriers would be prudent.

Concept for Underground Operations

For the sake of discussion, we can divide post-site-characterization underground activities at Yucca Mountain into a construction phase and an operations phase. The construction phase includes excavation of service tunnels, shafts, ramps, and emplacement tunnels and installation of ground support, rails, power systems, and instruments in the excavated openings. Operations-phase activities include underground transportation of waste, waste emplacement, waste retrieval, and underground maintenance, monitoring, and performance confirmation. The two phases will overlap considerably because emplacement tunnels will be constructed throughout the waste emplacement process. The construction phase will begin after the NRC authorizes construction and will last approximately 40 years. The operations phase will begin approximately 6 years after the construction phase starts and will last more than 100 years.

As currently configured, the waste emplacement tunnels will be spaced approximately 22 meters (70 feet) apart and will be between 5 and 5.5 meters (16 to 18 feet) in diameter. They will contain waste packages that are not fully shielded (from 35 to 60 rem/hour at the package surface).³¹ Normally, the doors of each emplacement tunnel would be closed after the tunnel is loaded with waste. Since there will be essentially no ventilation, the tunnel walls could reach 200°C (392°F) within 50 years.

As discussed by the Board (NWTRB 1995a), the DOE adopted an approach to repository design, called the "focused development approach," in early 1994. A hallmark of this approach is moving forward with a single design for the underground and surface parts of the repository and

³¹ The allowable dose for a worker is 5 rem/yr (see 10 CFR Part 20).

for the waste package. The focused development approach is risky because there is no fallback position if the single design being pursued turns out to be marginal or unacceptable. This is especially the case if the assumptions supporting the design (e.g., a dry repository) turn out to be unsupportable.

A key assumption of the DOE's concept for underground operations is that there will be no human entry into an emplacement tunnel when it contains spent fuel or high-level waste.³² Excluding humans means that all operations must be performed remotely. The Board has concerns about the dependability of a remotely operated system, especially the delays, costs, and safety in recovering from mechanical breakdowns or other events. This scheme probably can be implemented, but it may add unnecessary complexity and cost to repository development. In any case, it will require a program for developing and demonstrating equipment for spent-fuel and high-level-waste operations.

The Board believes that alternative concepts for underground operations should be developed and examined. This should begin immediately so that any alternatives that appear feasible and practical may be considered in the VA. At least one of the alternatives should be based on conservative application of existing technology, for example, shielding the waste packages so that human activity near them is possible and ventilating the emplacement tunnels to provide temperatures low enough for effective functioning of humans and machines, sensors, and other equipment. Such a radiation shield might serve a dual purpose as a seepage shield. Ventilation may help to remove water from the repository, rather than having it condense above and later percolate down through the repository. Ventilation also may reduce thermal effects in the repository. A thorough and objective evaluation of such a "low technology" alternative is needed for comparison with the more "high technology" remote-operations concept.

Repository Layout and Design Alternatives

The underground part of the March 1996 repository ACD consisted of two repository areas separated by the Ghost Dance Fault. The two waste emplacement areas provided

³² Key controlled design assumption #13 is, "No human entry is planned in emplacement tunnels while waste packages are present. The waste emplacement/retrieval equipment may use robotics and/or remote control features to perform operations and monitoring within the emplacement tunnels. Under off-normal conditions, human entry will be considered if protection to the workers can be provided." (TRW 1995b).

a total repository area of about 486 hectares (1,200 acres).

The repository layout continued to evolve later in 1996. For example, data obtained from the ESF late in 1995 showed the Drill Hole Wash Fault to be a very minor feature in the area north of the Ghost Dance Fault. Combined with the decision to base the repository conceptual design on a high loading (83 MTU/acre), this discovery allowed the repository area west of the Ghost Dance Fault to be expanded northward, eliminating the need for the other area. Now, all of the repository is on the same level west of the Ghost Dance Fault (and the ESF main tunnel), greatly simplifying layout of the repository.

As of the end of 1996, the repository area is bounded on the east by the Ghost Dance Fault, on the west by the Solitario Canyon Fault, and on the south by where the repository horizon (TSw2) becomes too shallow and thin. The area where wastes would be emplaced is approximately 340 hectares (840 acres). Including areas not used for waste emplacement (e.g., service tunnels), the overall repository is approximately 1 kilometer wide and 5 kilometers long (500 hectares, or 1,200 acres). Conceptual designs show that it can hold approximately 11,000 waste packages containing 70,000 metric tons of high-level radioactive waste and spent fuel, the initial repository capacity specified by Congress.

As now conceived, the layout of the repository incorporates the ESF main tunnel as a service tunnel on the repository's eastern edge. A 7.6 meter (25 foot) service tunnel will be excavated on the western edge, as will a north-south ventilation tunnel along the center of the area about 10 meters (33 feet) below the repository level. Approximately 160 waste emplacement tunnels will be excavated in a generally east-west direction across the area, bounded by the east and west service tunnels. The exact orientation of the waste emplacement tunnels will be determined after additional exploratory data showing joint set (rock fracture) orientation in the emplacement area are obtained.

The waste emplacement tunnels are planned to be up to 1,200 meters (4,000 feet) long and accessible for waste emplacement from both ends. Ventilation shafts will be provided for two independent ventilation systems, allowing ventilation for the construction area to be isolated from that for the waste-handling areas. The ESF north ramp will be used for waste emplacement access and the south ramp for construction access and removal of excavated rock.

The long-term waste-isolation functions of a repository also may influence its design. Several years ago, the DOE assembled a single set of design assumptions that did *not* include alternatives such as backfill in waste-emplacements tunnels or low thermal loading. Now, any consideration of alternatives is treated as an “add-on” modification to the existing design. Not surprisingly, when alternatives are investigated as add-ons to the existing design rather than as features of designs that are integrated with the alternatives, they often are found to be prohibitively expensive. A credible analysis should be made of design alternatives (e.g., need for backfill) that may lead to fundamentally different repository designs. “Force-fitting” alternatives onto an existing design with which they may be incompatible is not an effective way to evaluate their merits.

Construction Planning

Construction planning consists of defining the methods of excavation, ground support, ventilation, removal of excavated rock, and logistical support and the sequence of activities of the construction process. After the NRC issues the operating license, construction sequencing must be coordinated and separated from the simultaneous emplacement of waste packages in the completed part of the repository.

Excavation

One of the first repository-design issues addressed by the board of consultants in 1996 was the ACD proposal for designing and developing new TBMs for constructing the approximately 200 km (120 miles) of emplacement tunnels. The board of consultants strongly recommended against developing a new TBM and in favor of a TBM of standard design — a full-face, short, lightweight, maneuverable machine. This type of machine has evolved over four decades, is standard equipment in underground construction, and has been shown to be reliable, flexible, and cost-effective for tunneling in a wide range of rock types and qualities. Special TBM features, if any, would be defined by the contractor selected to construct the repository.

Construction of turn-outs from the service tunnels to each waste emplacement tunnel (for allowing a rail vehicle to deliver a shielded waste package to the portal at each end of a waste emplacement tunnel) poses a special excavation problem. This type of excavation is not readily performed by full-face TBMs, but other mechanical excava-

tion equipment (referred to generically as “roadheaders”) can be used. Although relatively inefficient in hard rock (such as the repository geologic strata), roadheader technology is improving and is preferable to using explosives because it causes less damage to the surrounding rock and is less disruptive of other operations.

Ground Support

An important element in designing and constructing the underground repository is ground support for the waste emplacement tunnels. Providing and maintaining stable tunnels for waste emplacement will be a major item in the cost of the repository. After the repository is closed, the waste packages are to provide containment for “thousands of years.” Early collapse of the waste emplacement tunnels during the post-closure period could alter the assumed environment for, and integrity of, the waste packages and introduce an additional uncertainty in the expected containment period.

To provide both preclosure and post-closure stability for the waste emplacement tunnels, three ground support techniques have been identified by the DOE, in consultation with the board of consultants, that may apply to expected rock conditions and tunnel size. The techniques consist of expanded precast-concrete segments, cast-in-place concrete, and steel sets. Steel sets are used traditionally in tunnel construction as temporary support until a permanent cast-in-place concrete liner can be installed.³³ Steel sets are circular steel ribs, usually manufactured from light steel I-beams, placed perhaps a meter apart and wedged tightly against the rock. The rock between the sets is supported by steel mesh or plates (lagging) that bridge the gap between adjacent sets. Because of the long service life required of the repository ground support (more than 100 years), steel sets may prove inadequate, and a concrete liner may be needed.

Expanded tunnel-lining segments of precast concrete consist of manufactured segments placed in rings, perhaps a meter wide, just behind the TBM as the tunnel is being excavated. Each ring segment is held in place by the wedging action of the last segment. This type of liner allows a single excavation-and-lining operation for tunnel construction, improving efficiency.

³³ The need, if any, to replace steel sets in the ESF with a concrete liner has not been determined.

As recommended by the board of consultants, an expanded precast-concrete liner is the most favored technique for lining tunnels in a Yucca Mountain repository. This approach introduces the lowest quantity of cementitious materials of any approach using concrete.³⁴ The segments can be thin (several inches), with or without reinforcing, and can be manufactured to high dimensional tolerances. The liner is flexible and can maintain structural integrity when the tunnel shape is deformed because of nonuniform loading that could result from thermal or other effects. The natural creep characteristics of concrete (the tendency to deform under load over long periods) may limit thermally induced stresses in the concrete.

The alternative to precast liners is a cast-in-place concrete liner. This is done as a two-pass operation. First, the tunnel is excavated using rockbolts or steel sets as temporary ground support to provide a safe opening. After excavation has been completed, a concrete lining is pumped into place and cured behind a movable form.

The recent concerns expressed about the postulated undesirable effects of an alkaline pH, which could result from the use of cementitious materials in the waste emplacement tunnels, would have to be balanced against the drawbacks of the only alternative ground support technique not using concrete: steel sets and lagging.

An additional concern is the need for detailed geologic mapping of the emplacement tunnels, which might be difficult using precast segments.³⁵ This would have to be evaluated against limited geologic mapping, relatively massive use of concrete in a cast-in-place operation, or use of steel sets and lagging. Normally, depending on tunnel size, cast-in-place concrete must be approximately 20 to 30 cm (8 to 12 in) thick to ensure adequate support because of construction tolerances.

As previously stated, steel sets and lagging used in underground construction are considered temporary until per-

manent support can be installed. The ability of a steel-set-and-lagging ground support technique to be effective for the preclosure period requires considerable extrapolation of industry experience, particularly when considering the thermal environment and the difficulty of performing maintenance in the waste emplacement tunnels. To assume that the steel sets and lagging would function for any period beyond repository closure is, at best, highly speculative.

A final concern related to ground support is the need, if any, for documenting quality assurance of the ground support system that is used. This is of concern because of the high cost of documenting compliance with quality assurance requirements. Ensuring the quality of steel sets and precast-concrete liners, which are manufactured in a controlled environment, may be somewhat easier than ensuring the quality of a cast-in-place liner, but the cost differences, if any, are unknown.

Construction Sequence

A factor that is very important for estimating the cost of repository construction is the sequence of excavation operations and the removal of excavated rock. A concept being considered is to construct first the repository north-south service and ventilation tunnels, the ventilation shafts, and all connecting accesses and tunnels. Then, four east-west waste emplacement tunnels will be excavated, spaced equally apart, across the repository area. The four tunnels will be connected by short shafts to the ventilation tunnel beneath the repository. The remaining waste emplacement tunnels will be excavated sequentially, starting at the north, and excavated rock will be removed by conveyor along the ventilation tunnel and up the south ramp to the surface.

Since entering the repository strata, TBM operations have generated dust problems. OSHA regulations place a limit on dust that contains silica in the form of the mineral cristobalite. The DOE, through a memorandum of understanding with OSHA, is required to enforce all OSHA standards. To prevent risks to underground construction personnel, the DOE now requires the use of full-face respirators, which has had a detrimental effect on construction productivity and may reduce worker safety in other ways by interfering with vision and communication between workers. Proper construction planning, including consideration of ventilation, removal of the excavated rock, TBM design, and procedures for installing ground support, will be needed for repository excavation to mitigate or eliminate dust levels that require full-face respirators.

³⁴ Concrete or other cementitious materials may alter the chemical characteristics of water in and near the repository, thereby affecting the solubility and mobility of radionuclides. Minimizing use of cementitious materials may be desirable if changes are expected to be significant.

³⁵ Tape records of automated television scanning of the tunnel surface ahead of precast insertions may offer adequate information on emplacement tunnels.

Repository Design: Summary

Designing the repository is an essential starting point for developing all four components of the VA. Although there is no need to have the designs optimized at the time of the VA, they should be integrated and contribute to waste isolation. It is important that the design be flexible enough that it can take advantage of new essential information and developments as they become available after the VA. New technology elements of the designs (if any) should be identified, and the necessary research, development, and demonstration programs should be described and the costs estimated. If existing technologies can be used in lieu of developing new ones, especially ones involving remote operations, their merits should be examined as part of the VA.

Over the last year, the DOE has made dramatic progress in developing a conceptual design for the underground parts of the repository. A rudimentary operational strategy is evolving, consideration is being given to the activities required during the very expensive 100-year operation and maintenance period, and some thought has been given to meeting regulatory requirements for confirmatory testing.³⁶

The repository conceptual design and total system life-cycle cost estimate to be developed for the VA in 1998 will require a much more mature operational strategy, including failure-mode analyses and operational redundancies. If, as shown in the 1996 ACD, approximately 75 percent of the total repository cost will be operation and maintenance, the DOE should seek simpler and less expensive alternative conceptual designs. These considerations must be clear elements in arriving at the licensing design.

For example, at the July 1995 Board meeting (NWTRB 1995b), the DOE presented a conceptual repository layout that included a center (bisecting) service tunnel for the part of the repository west of the Ghost Dance Fault (now the entire repository). This center service tunnel, which was at the same level as the repository, was to reduce the effective length of the waste emplacement tunnels from 1,200 to 600 meters (4,000 to 2,000 feet). The modification reduced the "reach" that would be required from each end of the bisected tunnels to 300 meters (1,000 feet). This modification could greatly simplify some operation and maintenance activities while adding complexity to repository

construction. Apparently, this reduction in the length of waste emplacement tunnels has been abandoned, although the reason for the change has not been documented.

Thermal-Loading Strategy

The issue of the appropriate repository thermal loading has long been of concern to the Board. Areal thermal loading (or areal mass loading), the thermal output of the spent fuel per unit area of the repository, has a direct effect on almost all aspects of the design and safety of the repository. Understanding of this issue has improved appreciably and, with *in situ* thermal testing now under way, we expect the knowledge to continue improving.

Early in fiscal year 1995, the DOE directed repository designers to proceed assuming a high thermal-loading (high-temperature) strategy but not precluding the option to revert to a lower thermal load if test data invalidate the use of the high-temperature regime. Adopting a thermal loading of approximately 83 MTU/acre will allow the full 70,000 metric tons of high-level waste and spent fuel to fit easily into the portion of the proposed Yucca Mountain repository west of the Ghost Dance Fault.

Two governing thermal goals adopted for the design of the hot repository were that the maximum temperature of the spent fuel in the waste packages not exceed 350°C and that the maximum temperature of the host rock not exceed 200°C. These limits were devised to prevent the possibility of damage to the zircaloy cladding of the fuel rods and the possibility of phase changes in minerals in the repository host rock. Phase changes in minerals could be detrimental to the rock's structural integrity and the stability of the tunnels. (For more information on thermal management, see NWTRB 1992 and subsequent reports.)

Current assumptions for repository design (TRW 1996a) that affect waste-package and rock temperatures are (1) backfill will not be placed around the waste packages at repository closure, (2) there will not be continuous ventilation of the emplacement tunnels during the preclosure period, and (3) the majority of the waste packages will contain up to 21 spent-fuel assemblies from pressurized water reactors.

The repository ACD uses equidistant placement of waste packages (point thermal load). Waste packages are placed approximately 22 meters (70 feet) apart, center-to-center, the same as the spacing of the waste emplacement tunnels.

³⁶ See 10 CFR 60.137, performance confirmation program.

The thermal output of waste packages could vary appreciably, depending on their contents. Some packages containing vitrified high-level waste from Savannah River might have a thermal output approaching zero, whereas some waste packages containing spent fuel from commercial reactors might have thermal outputs of 18 to 20 kW. Some adjustment in the thermal output of waste packages could occur at the repository surface facility by "mixing and matching" during loading of the waste packages, but safety concerns may keep such hot-cell operations to a minimum.

An alternative spacing strategy being considered, called "thermal line-loading," places the waste packages close together and increases the spacing of the tunnels to maintain the same areal thermal loading. The line-loading strategy provides a more uniform temperature along the length of the tunnel, a dramatic decrease in tunnel length and an associated reduction in construction cost (currently estimated to be approximately \$700 million), higher rock temperatures, and a longer period before the boiling isotherms coalesce between adjacent tunnels.

Since the DOE's decision in late 1994 to proceed with the ACD assuming a high thermal-loading strategy, little progress has been made in evaluating alternative strategies for repository thermal management. For example, evaluations have indicated that a low-temperature repository (all rock temperatures below boiling) could be designed without increasing the current area if the repository is ventilated continuously and lower maximum thermal output is assumed for the waste packages. However, when examined as an add-on, the repository ACD-controlled design assumptions require a repository area of approximately 3,000 acres — a conclusion that would mandate a high-temperature thermal-loading strategy because of site-characterization limitations.

We are also left with the question of what a repository conceptual design would be if the controlled design assumptions were to include a reduced maximum thermal output for waste packages and passive ventilation, by natural convection, of all waste emplacement tunnels until repository closure. Would maximum rock temperatures be below boiling? Would the total repository life-cycle cost be less than the ACD estimate? Would such a configuration provide greater long-term safety if the assumed moisture percolation flux reaches levels of 10 mm/year or more?

Engineered Barrier System

Robust Engineered Barriers

The waste package³⁷ may be thought of as a series of barriers that surround the radioactive waste materials, prevent or retard water from reaching the materials, and prevent or retard the passage of radionuclides from the waste package to the near and more remote environment. The waste package is an important part of the engineered barrier system.

The Board strongly endorses the concept of "defense-in-depth" for isolating radioactive wastes in a repository. Defense-in-depth can be achieved through the use of multiple and redundant individual barriers that have safety-performance attributes that are affected by different mechanisms or events. Adding barriers to ensure the integrity of the repository would seem to be a prudent move.

Before 1993, the DOE's reference concept of a spent-fuel waste package was not robust; it consisted of little more than a thin-walled metal container that could hold several spent-fuel assemblies. The waste packages were to be buried a few meters below the floors of repository tunnels. In 1993, the DOE embraced the current, and much different, concept for waste packages, one that contains many more spent-fuel assemblies and has two walls, each thicker than the wall in the original concept, the outer wall being much thicker. In addition, the waste package would be placed on the tunnel floor or in a low cradle above the floor rather than in boreholes.

The Board is pleased that the DOE now has a more robust waste package. The move from a single wall to a double wall increased robustness because it added a barrier. Likewise, the move to thicker walls increased robustness because it prolonged the life of the walls. There are both trade-offs and limits to adding barriers, however. For example, adding too many barriers could have an insulating effect that could result in temperatures so high in the center of a spent-fuel waste package that the capability of the zircaloy cladding to act as a barrier could be compromised. Cost also is an important limit. When to add (or forgo) barriers could be a difficult, subjective, and contentious judgment if the criteria for doing so are not set carefully.

³⁷ "Waste package" means the waste form and containers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container. "Waste form" means the radioactive waste materials and encapsulating or stabilizing matrix.

The current reference design for spent-fuel waste packages has at least four barriers. See Figure 5. From inside out, the barriers for a waste package containing commercial light-water spent-fuel assemblies are as follow (primary barrier functions are in parentheses):

1. The ceramic uranium oxide spent-fuel pellets (limit the release rate of radionuclides).
2. The cladding, usually zircaloy, on each fuel rod (prevents contact of the pellets by air and water, prevents escape of gaseous fission products).
3. The nickel-alloy inner wall of the waste container (excludes air and water).
4. The carbon-steel outer wall of the waste container (excludes air and water, provides cathodic protection to the inner wall, provides structural strength).

Helping make the current reference design for waste packages robust is the fact that the individual barriers must fail sequentially for water to reach the radionuclides in the spent fuel — an inner barrier cannot begin to degrade until the barrier immediately outside it has failed. Another factor aiding robustness is that the barriers are composed of different materials and therefore are likely to fail by different mechanisms.

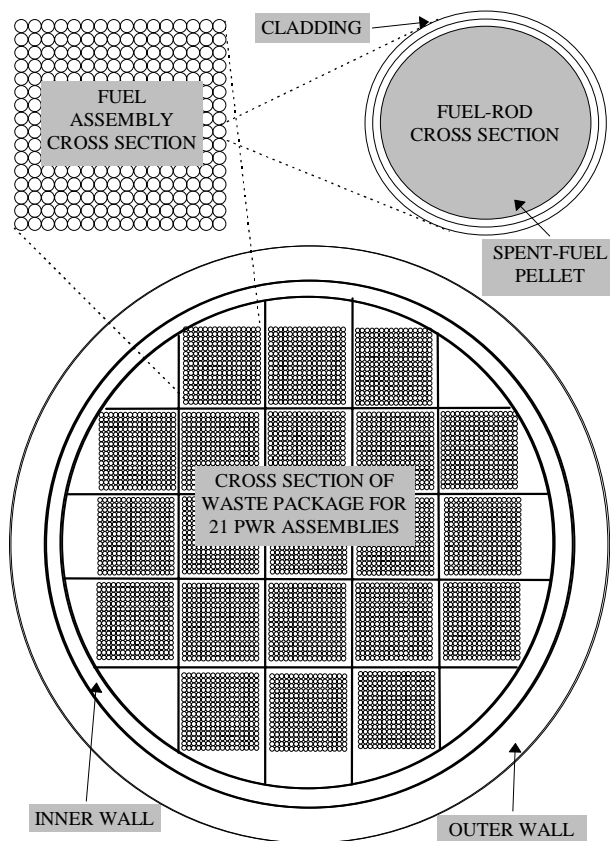


Figure 5. Illustration of 21-PWR Spent-Fuel Waste Package

Since the current waste package design was adopted, the amount of water estimated to seep into the drifts has increased significantly. Furthermore, essentially *no* data have been obtained from the area west of the ESF where the waste will be emplaced. If such data were generated, uncertainties in the current estimates of the magnitude and distribution of seepage into the waste emplacement area perhaps could be reduced. At the current level of uncertainty about percolation flux and distribution, prudence dictates giving serious consideration to adding engineered barriers to the waste packages.

There are additional barriers that could improve waste package performance. Three examples are discussed below: fillers, drip shields, and engineered inverts.

Fillers

Solid materials added to the waste package to fill void spaces within and between the fuel assemblies are called “fillers.” Examples of materials that can be used as fillers are steel shot, borosilicate glass beads, and depleted uranium oxide particles. The current waste package design does not incorporate fillers. The potential advantages of fillers include providing additional structural support inside the waste package, reacting with and sequestering certain radionuclides, providing additional shielding, and retarding the flow of water to and from the waste form. Fillers containing certain materials, such as boron or depleted uranium, can provide long-term protection against accidental formation of a “critical mass” which could lead to a “criticality,” that is, a self-sustaining nuclear fission reaction. The added structural strength would reduce the size of water-collecting depressions over the spent fuel after the package is crushed.

Before the DOE’s MPC contract was canceled at the beginning of 1996, a significant disadvantage of fillers was thought to be the requirement for adding them to waste packages at many different reactor sites. Now, however, the design basis for the surface facilities at the repository is changing to one in which most spent fuel is repackaged at the repository, effectively eliminating this disadvantage or at least reducing its significance.

Within the DOE program, fillers have been the subject of several small engineering studies performed by the waste package engineering group, and experiments have been conducted on filler materials and the mechanics of adding fillers to waste packages. A truly comprehensive study of

filler use has not been done, however, and clearly is warranted. The study should include examination of the changes in repository design and operation necessary to accommodate efficient filler use and the effect of filler use on total system performance and cost.

Drip Shields

Drip shields are impervious structures placed over a waste package to prevent water from contacting the package. The current waste package design does not include a drip shield. The M&O examined the potential performance benefits of drip shields as a small part of a large systems study (TRW 1996b) conducted during fiscal year 1996 on the engineered barrier system. The examination indicated that long-lived drip shields can delay the release of nongaseous radionuclides for a period approximately equal to the lifetime of the drip shields. However, unless drip shields are very long-lived — on the order of 750,000 years — they will not reduce the peak dose to an individual in the accessible environment.

However, the fiscal year 1996 systems study assumed a percolation flux at the repository level significantly lower than now thought likely and did not use the most conservative assumptions about the fraction of the total percolation flux that would contact the waste packages. Furthermore, the drip shields were examined only in conjunction with the use of backfill, and the study apparently addressed only drip shields consisting of a thin sheet of titanium or a ceramic material.

Just as for fillers, a *comprehensive* study of drip shields is warranted. The study should include examination of the changes in repository design and operation necessary to accommodate effective use of drip shields and the effect of drip shields on total system performance and cost. The performance assessment should include scenarios based on a wetter repository and more conservative assumptions about the fraction of water contacting the waste packages. The drip shields examined should include not only titanium and ceramic ones, but also alternatives, such as thick reinforced-concrete drip shields, which might be combined with the roof support system or radiation shield. The study should consider both a backfilled repository and a ventilated one. Although the drip shields may offer short-term benefits, the key concern is their ability to perform over the long term. If the study shows an improvement in waste isolation at justifiable cost, drip shields should be made a

part of the waste package reference design, at least until better understanding of the hydrology of the unsaturated zone at Yucca Mountain is attained.

Engineered Inverts

The invert is simply the floor of a tunnel. A TBM creates an excavation with a round cross section. To form a level surface for ease of movement, the floor of a tunnel may be built up with materials such as concrete or crushed tuff. At the same time, the invert could incorporate materials that contribute to the long-term performance of a repository. For example, many readily available and inexpensive materials, such as phosphate rock, bind tightly with the actinide elements in spent fuel. Placing a few cubic meters³⁸ under each waste package could delay, if not halt, such radionuclide migration before it starts. Other materials (e.g., depleted uranium) could be added to the inverts to allay concerns about external criticality. Simplicity and low cost should make engineered inverts prime candidates for evaluation as additional barriers.

In summary, comprehensive studies of fillers, drip shields, and engineered inverts are clearly warranted. The studies should include examination of the changes in design and operation of repository surface and underground facilities that would be necessary to accommodate efficient and effective use of fillers, drip shields, and engineered inverts as additional barriers. The studies also should examine the effect of additional barriers on total system performance and cost. The performance assessments should include scenarios based on a wetter repository and more conservative assumptions about the fraction of water seeping through tunnel roofs immediately above waste packages. The studies should include both ventilated and backfilled underground facilities. If the study shows a clear improvement in potential performance at justifiable cost, the use of fillers, drip shields, or engineered inverts should be adopted as part of the waste package reference design, and the repository design and the operations plan should be changed accordingly.

Waste Package Design

The basic concept for the waste package — large capacity, tunnel-emplaced, and multiwall — has remained the same for several years. Specific waste package designs, how-

³⁸ For some materials, such as phosphate rock, a few percent of the material mixed with crushed tuff might be adequate to form a substantial engineered barrier.

ever, continue to evolve. For example, there already are several changes since the ACD was issued in March 1996.

A very significant change is the increase in importance of the so-called “uncanistered fuel” waste package. This is the waste package into which fuel assemblies are loaded individually *at the repository’s surface facility*. The change is a direct consequence of canceling the procurement of the MPC early in 1996. Before the cancellation, the design assumption was that a large majority of commercial spent fuel would arrive at the repository in an MPC that would need only transfer to a disposal overpack. Since the cancellation, the design assumption has been that a large majority of commercial fuel will arrive at the repository in transportation casks or in dual-purpose (storage and transportation) canisters with transportation overpacks, thus requiring transfer, assembly-by-assembly, to the uncanistered-fuel waste package.

Other changes include using carbon steel for the basket of the uncanistered-fuel waste package rather than more expensive materials, such as stainless steel. This is possible because of the use of dry transfer operations at the repository’s surface facility. Carbon steel is not recommended for wet transfer operations because even minor amounts of rust can contaminate the transfer pools and make cleaning the exteriors of the waste packages difficult. Carbon steel is cheaper than stainless steel and has better thermal conductivity. In addition, the material of the waste package inner wall was changed from Alloy 825 to Alloy 625, which has a higher nickel content. Alloy 625 is more expensive than Alloy 825 but is more corrosion resistant. Alloy 625 was not in the long-term corrosion program at Lawrence Livermore National Laboratory but was added to it quickly. Another change was replacing the copper-nickel outer wall material of the waste disposal package for defense high-level wastes with carbon steel. This should save money and have a negligible effect on performance.

Another change is the proposed manufacturing technique for achieving good contact between the inner and outer walls. Good contact is desirable for the outer wall to provide broad cathodic protection to the inner wall. Primarily because of cost, the M&O has shifted its focus from using weld overlay for constructing the inner wall (by depositing Alloy 625 weld metal on the inner surface of the outer wall) to shrink-fitting the outer wall over the inner wall (by inserting a cold inner wall into a heated outer wall). The long-term research program at Lawrence Livermore National Laboratory on corrosion must be configured to

yield knowledge of the long-term effects that the residual stresses from the shrink-fitting operations may have on the corrosion performance of a waste package in a repository. Pursuing the shrink-fitting approach is a good idea; at the same time, more-conventional alternatives, such as loose-fitting inner and outer walls with some means of providing good contact between the two, should be pursued with equal diligence.

If the waste packages in a repository are fully shielded, humans can work near them to perform maintenance, monitoring, performance confirmation, inspection, retrieval, and other functions without exceeding radiation-dose limits. The M&O made a very brief presentation on two concepts for fully shielded waste packages to the Board at its October 1996 meeting in Arlington, Virginia. The concepts were 8-inch-thick special concrete with stainless steel sheathing and 18-inch-thick carbon steel. The Board concluded from the presentation that fully shielded waste packages are clearly technically feasible. However, the incremental costs presented for the two full-shielding concepts were substantial and could prove prohibitive.

The Board believes that fully effective but less expensive shielding designs are possible and urges the DOE to make the effort to identify them. In particular, the Board believes that the issue of shielding is a good example of where a true systems approach is needed. Shielding should not be examined solely as an add-on feature to an existing design. Instead, any examination of shielding should be done in an integrated context that considers waste package design, repository design, and the repository operational concept together. In other words, incremental costs associated with the shielding itself could be partially or entirely balanced by savings in repository capital and operating costs.

Conclusions and Recommendations

Conclusions

1. The DOE needs to formulate a plan for implementing the concept of remote underground operations. Actual development and demonstration of the equipment needed for the concept can be delayed several years.
2. At the current level of uncertainty about water flow and distribution, prudence dictates seriously considering adding engineered barriers to ensure the integrity of the repository system. There are many potential additional barriers that could improve waste package performance.

3. Because only one set of controlled design assumptions was developed, only one repository concept has been developed.
4. Maintaining tunnel stability during the 100-year retrievability period will pose a significant challenge.

Recommendations

1. The DOE should develop and examine alternative concepts to the proposed remote underground repository operations, for example, ventilation of emplacement tunnels and shields for waste packages. Some alternatives should be developed in time for consideration in the viability assessment.
2. The DOE should evaluate alternative design assumptions to determine whether enhanced repository performance or improved operations can be achieved cost-effectively.
3. The DOE should evaluate the use of precast or cast-in-place concrete tunnel liners to achieve adequate long-term tunnel support. The evaluation should consider cost and possible effects on waste isolation.
4. Given the inevitable uncertainties about repository performance, more attention to defense-in-depth (multiple, redundant barriers) is needed in the waste package and repository designs. In particular, *comprehensive* studies of alternative engineered barriers — such as fillers, backfill materials, drip shields, and engineered inverts — should be completed.

Chapter 4

Recent Board Activities

International Exchange of Information

The Board seeks to increase its knowledge and understanding of the problems shared by other nations as they try to find safe ways to dispose of spent nuclear fuel and high-level waste. To learn from work under way in other countries, the Board participated in several information exchanges during 1996.

During the Board's winter meeting in January in Las Vegas, Nevada (NWTRB 1996a), representatives of the nuclear waste management programs in the United Kingdom and in the People's Republic of China were invited to brief the Board on developments in their respective programs. The Board was particularly interested in learning about the scientific and technical issues that were raised as part of a public inquiry in Cumbria County in England on the question of whether U.K. Nirex Ltd., should be authorized to build an underground research laboratory there. In addition, the Board extended its scope of inquiry for the first time beyond the programs of the developed countries by inviting a representative from the People's Republic of China. The Board's purpose was to learn about Chinese plans for researching a potential site in the Beishan area, which shares some climatological and environmental similarities with the site at Yucca Mountain.

United Kingdom

Michael Folger, chief executive of U.K. Nirex Ltd., provided an update on the British deep disposal program. The British government reaffirmed deep disposal as their national policy on July 4, 1996. Their timetable for establishing a repository depends on the scientific requirements for making a sound safety case. The current focus is on intermediate-level wastes (ILW) from fuel reprocessing. High-level waste is being converted to solid form and will be held for 50 years to cool down in a passively safe surface storage facility at Sellafield, which also is being investigated as a site for a potential underground repository for ILW. The current plan for disposal of high-level waste

would place disposal in a repository separate from the Sellafield ILW site. Research at Sellafield focuses on the geohydrology of the volcanic rock and sandstone overlay of the site, with emphasis on ground-water flow and dilution. Base-case modeling for the Sellafield geohydrology, taking into consideration the uncertainties inherent in the process, has indicated, so far, that the risks to individuals are within the parameters set by British health and regulatory agencies. The next step will be to build confidence in the site in order to establish a firm basis for either selecting it as the repository site or for looking elsewhere. This will involve a rock characterization facility (RCF), which will be a site-specific underground rock laboratory to be developed over 10 years at a planned depth of 650 to 900 meters (2,000 to 3,000 feet) below sea level.

In December 1994, a Nirex request for planning permission for the RCF was refused by the Cumbria County Council. A public inquiry was instituted to resolve this issue. The inquiry helped prevent the sensationalism that could have attended the siting of the RCF and generally resulted in a public that is more aware of the work being undertaken and of the high-quality science involved in making the safety case. *Mr. Folger attributed a great deal of these positive aspects to the use of expert judgment in probabilistic risk assessment and to making that process very transparent to the public.*

People's Republic of China

Dr. Ju Wang of the Beijing Research Institute of Geology (China National Nuclear Corporation) presented an overview of the Chinese nuclear program. China's nuclear industry was established in 1955, five years after the birth of the People's Republic. Currently, there are two operating nuclear power plants, and four more are planned over the next five years. By 2010, China plans to have 20,000 megawatts of nuclear power production capacity. Current national policy is to reprocess spent nuclear fuel.

Despite the early stages of development in the nuclear power program, China has made a commitment to developing plans for the eventual disposal of high-level waste. As in the rest of the world, plans are to dispose of the waste in a deep geologic repository. Five sites are being studied for locating a potential repository, comprising somewhat different geologic settings that include granite, granite and shale, granite and tuff, and mudstone with shale and granite. Waste disposal work is managed by the China National Nuclear Corporation, which also is responsible for transportation of spent nuclear fuel and high-level waste, reprocessing, vitrification, and final disposal. The Everclean Environment Engineering Co., a unit of the China National Nuclear Corporation, is responsible for selecting and characterizing disposals; repository design, construction, and operation; and repository closure and monitoring for all levels of nuclear waste. National and regional screening for site locations has been completed. District screening and preliminary site characterization are scheduled to be completed by 2010, final site characterization and suitability studies by 2023, repository design by 2029, and repository construction by 2050. Repository operations are scheduled to begin in 2051.

District screening since 1989 has resulted in the selection of a potential disposal site in northwest China, in the Beishan area in Gansu Province. The site is in granite and is approximately 3,000 to 6,000 feet above sea level in the northernmost part of the province. It is characterized by flat gobi (desert or near-desert plains), small hills, and relatively stable geologic faults. Although the water table is relatively deep, current plans call for disposal in the saturated zone. Geological work is just beginning, and construction of an underground rock laboratory is planned for 2030. Suitability studies will determine where in the Beishan area the final site will be.

Sweden

Review of the Swedish Research and Development Program. At the invitation of Dr. Camilla Odhnoff, Chair of KASAM,³⁹ a delegation of Board and staff members visited Sweden on March 11-15, 1996, to participate in a review of the Swedish research, development, and demon-

stration program for final disposal of spent fuel.

With nine boiling-water and three pressurized-water reactors, the Swedish nuclear power program is one-ninth the size of the U.S. program. The government has decided that spent fuel will be disposed of in deep geologic repositories and that utilities will be responsible for all costs of waste management, including storage, transportation, and disposal. Unlike in the United States, however, the utilities are responsible for building and operating the waste management system, and the government is responsible only for regulation and review. In 1976, the Swedish utilities created SKB, the Swedish Nuclear Fuel and Waste Management Company, to handle their waste management responsibilities. The SKB intends to begin disposing of spent fuel in a deep geologic repository in 2008.

Like the United States, Sweden has a nuclear waste fund. The fee is 0.023 Swedish crowns (a little more than 3 mills) per kW-hr. However, the Swedish fee pays for more activities than does the corresponding U.S. fee. In addition to the cost of transportation and deep disposal of spent nuclear fuel, the Swedish fund pays for centralized storage of spent fuel, power plant decommissioning, and low-level waste disposal.

Recent developments in the Swedish program. In May 1995, the Swedish government decided that communities being studied as possible hosts for a deep geologic repository should be allowed to receive grants from the nuclear waste fund of up to 2 million Swedish crowns (about \$300,000) per year per community. The purpose of such grants is to facilitate the public's ability to follow and assess the feasibility study.

In January 1996, KASAM and several other Swedish organizations sent a letter to the Swedish government recommending that a "national coordinator" be named to facilitate the siting process. Subsequently, Olof Söderberg, the vice chair of KASAM, was appointed to the position. Unlike the now-defunct position of U.S. negotiator, the position has no authority to negotiate a siting agreement.

Currently, the most critical part of the Swedish program is the siting process. In the 1970s and 1980s the SKB conducted geological site investigations. In 1992, the SKB approached all Swedish communities and asked if they were willing to discuss the possibility of taking part in the site-selection program. The SKB was especially interested in feasibility studies as a first step in the program. A pre-

³⁹ KASAM is the approximate counterpart to the NWTRB for the Swedish high-level waste program. The Board has cooperated with KASAM (and a predecessor organization) on topics of mutual interest for more than five years.

requisite of the studies was that they would be based on existing geological data and the potential effect on the community; no drilling would take place. Two municipalities, Storuman and Malå, volunteered for feasibility studies. In both communities, two fairly good-sized areas, approximately 50-100 square kilometers (1,250-2,500 acres), were identified as warranting further study. In September 1995, however, residents of Storuman voted overwhelmingly (70 percent) against pursuing the project. Recently, the municipal council of Malå decided that a referendum will be held in September 1997 to decide whether the SKB should be allowed to continue its work to find a suitable site within the municipality.

During this process, the SKB also had approached four municipalities with nuclear installations to determine if they were interested in pursuing a repository feasibility study. Three of the municipalities — Östhammar, Nyköping, and Oskarshamn — have decided to accept feasibility studies. The most recent decision came from the municipal council of Oskarshamn in the fall of 1996. Of note, the decision to proceed in Oskarshamn includes a list of conditions that must be met by the SKB and Sweden's safety authorities in connection with the feasibility studies. The fact that Oskarshamn decided to accept a feasibility study is significant because a number of other important nuclear waste facilities are located or are being built there. These include the CLAB facility, where spent nuclear fuel from all of Sweden's reactors is being stored, and a pilot encapsulation facility, where the SKB will demonstrate the encapsulation of spent nuclear fuel for final burial.

Chairman's Presentation to the ENS in Stockholm

In June 1996, Dr. John Cantlon, Chairman of the Board, was invited to make a presentation at Topseal '96, an international conference on nuclear waste management and disposal. The meeting was sponsored by the SKB and the European Nuclear Society. Dr. Cantlon highlighted the Board's views on the status of the U.S. program for managing and disposing of commercial spent nuclear fuel and provided a brief overview of the program's organization. He summarized the DOE's efforts to characterize the Yucca Mountain site and the development of a waste isolation strategy for the site. He also reviewed legislative and regulatory changes under consideration at the time and offered the Board's views on the technical implications of those possible changes. Copies of Dr. Cantlon's remarks are available from the Board.

Visit to River Mountains Tunnel

The city of Las Vegas constructed the River Mountains tunnel to supply the city with water from the Colorado River. The tunnel is 4.3 meters (14.25 feet) in diameter and approximately 6,100 meters (20,000 feet) in length — nearly the same length as the ESF at Yucca Mountain. The River Mountains tunnel was excavated using a TBM in welded and nonwelded rhyolitic tuffs that are similar to the tuffs at Yucca Mountain, although the River Mountains tuffs appear softer and less fractured. Excavation began in mid-December 1995 and was completed in May 1996. On April 1, while the tunnel was still under construction, members of the Board and the staff visited the River Mountains tunnel to see whether lessons could be learned for improving the efficiency of the Yucca Mountain excavations.

The River Mountains tunneling operations were clearly more efficient than those at Yucca Mountain. The cost of the River Mountains tunnel was approximately \$20 million, including a liner of cast-in-place concrete. The River Mountains tunnel was constructed in less than six months, compared with more than two years at Yucca Mountain.

Construction of a repository at Yucca Mountain would require excavating more than 100 miles of tunnels. Better excavation efficiency than evident to date at Yucca Mountain will be required. Examples such as the River Mountains tunnel may help the DOE improve the efficiency of its operations.

Presentation to the NRC

On July 30, 1996, Board Chairman John E. Cantlon and Board member Jared L. Cohon presented to the U.S. Nuclear Regulatory Commission the Board's independent perspective on the status of the Civilian Radioactive Waste Management Program. The presentation reviewed developments in the program during the preceding year and explained the Board's views on two key issues: (1) the distinction between a viability assessment and a determination of site suitability and (2) the Board's recommendation to explore the potential emplacement area by excavating an east-west tunnel across the candidate repository block. Both issues are discussed at length in Chapter 1 of this report.

Appendix A

Nuclear Waste Technical Review Board

Members

Dr. John E. Cantlon was first appointed in January 1989. He was reappointed as Chairman of the Board in May 1992. Dr. Cantlon is vice president emeritus of research and graduate studies and former dean of the graduate school at Michigan State University. His field of expertise is environmental science.

Dr. Clarence R. Allen was first appointed in January 1989. He was reappointed to the Board in May 1992. Dr. Allen is professor emeritus of geology and geophysics in the seismological laboratory at the California Institute of Technology, Pasadena.

Mr. John W. Arendt was appointed to the Board in June 1995. He is the senior consultant and founder of John W. Arendt Associates, Inc., a registered professional engineer, and a certified nuclear materials manager.

Dr. Garry D. Brewer was appointed to the Board in May 1992. He is professor of resource policy and management at the University of Michigan in Ann Arbor. Dr. Brewer's expertise is public policy.

Dr. Jared L. Cohon was appointed to the Board in June 1995. He is dean of the School of Forestry and Environmental Studies and professor of environmental systems analysis and mechanical engineering at Yale University.

Dr. Edward J. Cording was appointed to the Board in June 1992. Dr. Cording is professor of civil engineering at the University of Illinois at Urbana-Champaign. His expertise lies in the area of geotechnical engineering and applied rock and soil mechanics.

*Dr. Patrick A. Domenico** was appointed to the Board in May 1990. He currently is the David B. Harris Professor of Geology at Texas A&M University, College Station, Texas. Dr. Domenico's area of expertise is ground-water hydrology.

Dr. Donald Langmuir was first appointed to the Board in January 1989. He was reappointed in June 1992. Dr. Langmuir is professor emeritus of geochemistry in the Department of Chemistry and Geochemistry at the Colorado School of Mines in Golden.

Dr. John J. McKetta, Jr. was appointed to the Board in February 1992. Dr. McKetta is the Joe C. Walter Professor of Chemical Engineering emeritus at the University of Texas, Austin.

*Dr. Ellis D. Verink, Jr.** was first appointed to the Board in January 1989. He was reappointed in October 1990. Dr. Verink is Distinguished Service Professor emeritus of Metallurgy and former chair of the Department of Materials Science and Engineering of the University of Florida, Gainesville. His areas of expertise are materials selection and corrosion.

Dr. Jeffrey J. Wong was appointed to the Board in June 1995. He is chief of the Human and Ecological Risk Division of the Department of Toxic Substances Control, California Environmental Protection Agency.

**Term expired on April 19, 1994; continued as a consultant pending Presidential appointment of a replacement.*

Appendix C

Meeting List for 1996-1997

January 9, 1996

Board Business Meeting *Las Vegas, NV*
Minutes available

January 10-11, 1996

Full Board Meeting *Las Vegas, NV*
Topics: Defense waste plan for Yucca Mountain, disposition of surplus weapons plutonium, use of expert judgment, EPA/NRC response to NAS standards, fiscal year 1996 program priorities, and outyear study plans, update on ESF and surface-based testing.

January 12, 1996

Tour of Yucca Mountain/TBM operations
Las Vegas, NV

April 29, 1996

Board Business Meeting *Austin, TX*
Minutes available

April 30-May 1, 1996

Full Board Meeting *Austin, TX*
Topics: TSLCC analysis, repository design update, update on results/findings from science and testing programs - surface/underground.

July 8, 1996

Board Business Meeting *Denver, CO*
Minutes available

July 9-10, 1996

Full Board Meeting *Denver, CO*
Topics: ESF activities and scientific studies, waste isolation strategy, climate and its relationship to Yucca Mountain hydrology.

October 9-10, 1996

Full Board Meeting *Arlington, VA*
Topics: Planned activities during fiscal year 1997, unsaturated zone flow at Yucca Mountain, concept of repository operations and effects on design.

October 11, 1996

Board Business Meeting *Arlington, VA*
Minutes available

Appendix D

Department of Energy Responses to the Recommendations in the Board's Reports

As part of its effort to keep the Nuclear Waste Technical Review Board informed of its progress, the Department of Energy (DOE) submits a summary of initial responses to recommendations the Board makes in its reports. Included here are the DOE's responses to the recommendations of the NWTRB's 1995 summary report. Inclusion of the DOE's responses does not imply Board concurrence.

[Insert DOE cover letter here.]

[The second page of the DOE cover letter goes here.]

**DOE Response to the Recommendations of
the Nuclear Waste Technical Review Board in its
1995 Summary Report to the U.S. Congress
and the Secretary of Energy, April 1996**

OVERVIEW RECOMMENDATIONS

Recommendation 1:

The DOE should continue to refine its waste isolation strategy to make it more robust, to address potential failure modes, to state the strategy's hypotheses more precisely, and to specify criteria for determining when those hypotheses have been validated or rejected.

Response:

The DOE is continuing to refine its Waste Containment and Isolation Strategy to make it more robust, to address potential failure modes, and to clearly state the strategy's hypotheses. The DOE expects the Waste Containment and Isolation Strategy to evolve as additional data are collected, and as analyses and performance assessments are completed. As the Program proceeds, the DOE will evaluate the relevant hypotheses to determine the degree to which they are confirmed, including the remaining uncertainty in the data and analyses related to their evaluation. Since, in general, the hypotheses are not subject to binary "validation or rejection," the DOE plans to use Total System Performance Assessment (TSPA) and related sensitivity studies to evaluate the degree to which the hypotheses are confirmed and the effect of the remaining uncertainty on the predicted repository performance.

Recommendation 2:

The DOE should evaluate what went wrong in the preparation and NAS review of its technical basis report on surface processes at Yucca Mountain.

Response:

The DOE has evaluated the process used to prepare its technical basis report on surface processes at Yucca Mountain and the National Academy of Sciences (NAS) review of this document. Even though technical basis reports are no longer being developed, the DOE will apply the lessons learned to refine and strengthen its future license application analyses. For example, some of the lessons learned include the importance of providing an adequate schedule for the preparation and review of documents, of increasing the role of project scientists in the preparation and review of regulatory documents, and of providing more detailed documentation to support the technical conclusions contained in the document. For the Project Integrated Safety Assessment (PISA), the appropriate line organizations will be responsible for the technical content, and the review will include the Principal Investigators, as appropriate. The DOE also has provided a realistic schedule for these activities. The final PISA will provide a complete and current site description that can be used to support compliance with DOE's revised siting guidelines.

Recommendation 3:

The DOE's safety demonstration for a repository should be as rigorous and thorough as practical at the time of the initial application for construction authorization. The DOE needs to continue to work with the NRC to determine an appropriate balance between the need for data and reliance on expert judgment.

Response:

If the Yucca Mountain site is suitable, the DOE intends to provide a defensible safety demonstration that is appropriate for the initial application for construction authorization. The DOE agrees that the safety demonstration should be as rigorous and thorough as practical, and must be supported by both field and laboratory data. The approach to preparing the license application recognizes that the NRC must have reasonable assurance that the repository will meet its performance objectives prior to authorizing construction. The DOE believes such assurance can be achieved through a safety demonstration supported by a focused site characterization program that is as comprehensive as practical.

To be acceptable to Congress and other stakeholders, however, the site characterization program must provide meaningful results within rational cost and schedule constraints. Consequently, the DOE must strike a balance between the collection and analysis of site data and the use of expert judgment to address the residual uncertainty in performance assessments in a way that facilitates regulatory decisions. It is inevitable that some uncertainties will exist at the time of construction authorization and for decades thereafter. Some uncertainties are likely to remain at the time of repository closure. Long-term testing, such as *in situ* thermal tests and material corrosion tests, will continue beyond the time of the initial license application as part of a performance confirmation program. The results of this testing will enhance confidence in the assumptions that are the basis for the performance assessments and other safety arguments in the license application.

The DOE is interacting with the NRC regarding the use of expert judgment and its utility in the licensing process. The DOE will not use expert judgment as a substitute for objective, quantitative analyses based on reasonably obtainable data that would measurably affect our understanding of repository system performance. Where appropriate mechanistic models are not available or the collected data lends itself to differing interpretations, however, we will use expert judgment to support technical conclusions. The elicitation of expert judgment associated with the recently completed Probabilistic Volcanic Hazard Assessment is an example of this approach.

RECOMMENDATIONS FOR RISK AND PERFORMANCE ANALYSIS

Recommendation 1:

Building on the strengths (and filling in the gaps) shown in TSPA-95, the DOE should prepare itself for the next, and critically important, role assigned to TSPA--the Yucca Mountain site "viability assessment" in 1998. Assumptions about models and input parameters will need to be highlighted and their bases clearly laid out and open for review.

Response:

The DOE is actively preparing for the upcoming Total System Performance Assessment (TSPA) in support of the viability assessment, which has been tentatively named TSPA-VA. This TSPA will incorporate directly the latest site and design information, including process models developed and documented by the site and design organizations. For each key process model, which would address key attributes identified in the Waste Containment and Isolation Strategy, a small working group will be formed consisting of representatives from both the Performance Assessment organization

and the organization responsible for the development, substantiation, and documentation of the process model. This process will ensure that: (1) all the key performance-related issues associated with each process model are adequately abstracted into the TSPA analyses; and (2) the technical bases used in the TSPA-VA analyses are clearly laid out and open for review. A detailed plan for the completion of the TSPA-VA is being prepared in the current fiscal year. The basic elements of this plan have been incorporated in DOE's Program Plan and have been implemented in the Long Range Plan/Integrated Project Schedule and the detailed planning for Fiscal Years 1997 and 1998.

As suggested by the Board and demonstrated in the succession of completed TSPA analyses, the intent of the next TSPA iteration will be to build on the information collected during previous iterations of the TSPA, as well as comments received from interested parties such as the NWTRB, the NRC, and the State of Nevada.

Recommendation 2:

TSPA should play an integral role in refining and testing the basic tenets of the developing waste isolation strategy. TSPA, for example, could provide an estimate of the amount of percolation flux that could, in turn, require a reexamination of the current strategy. It can also clarify what kinds of data are needed to demonstrate that the safety case has been made.

Response:

The DOE has used the earlier iterations of the TSPAs for the initial development of the Waste Containment and Isolation Strategy and for refining plans in the site and design programs. However, it is important to note that some assumptions in TSPA-1995 are not tied directly to substantiated conceptual models. Care must be taken not to over-interpret the results of TSPA-1995 nor to over-utilize these results in the allocation of testing priorities. TSPA is an iterative process that relies on updated and substantiated process models to provide greater confidence in the results. The DOE agrees that the results of current performance assessments in combination with sound technical judgment should be used to evaluate the hypotheses in the Waste Containment and Isolation Strategy and to prioritize testing needs. The DOE will continue to use the results of TSPAs and related sensitivity analyses to evaluate the degree to which hypotheses in the Waste Containment and Isolation Strategy are confirmed.

Recommendation 3:

The DOE should make an early determination of which aspects of the next TSPA will require expert judgment and make clear to the technical community how these judgments will be obtained.

Response:

The DOE agrees with this recommendation. During the ongoing planning process, the DOE's TSPA staff identified the following five process models that are potential candidates for the use of expert judgment for the next TSPA: unsaturated zone percolation flux; drift-scale thermal hydrology; long-term waste package degradation; waste form dissolution; and, saturated zone hydrology. These recommendations are being reviewed by the scientific and design programs to develop a prioritized list of expert judgment activities to support the next TSPA iteration. Agreement has been reached concerning the need for an expert elicitation regarding uncertainties in the unsaturated zone percolation flux model. Planning the details of this work is now in progress. The DOE has also issued a policy statement on the use of expert judgment entitled "Principles and Guidelines for Formal Use of Expert Judgment, Revision 0" (1995).

RECOMMENDATIONS FOR GEOENGINEERING

Recommendation 1:

The DOE needs to examine both the cost and the rate of progress for excavating the ESF and compare it with planned repository construction methods when assessing the viability of the Yucca Mountain site. Additional modifications to the TBM or use of a TBM of a different design may be needed to improve excavation efficiency.

Response:

Both the cost and the rates of progress for the various ground conditions encountered during excavation of the Exploratory Studies Facility (ESF) are available and will be utilized for planning and evaluating the repository construction methods. Lessons learned from the ESF design and construction will be used to maximize the effectiveness of the repository design associated with assessing the viability of the Yucca Mountain site. These lessons learned also will be used to determine the most efficient method of excavation, including the proper design of the tunnel boring machine(s).

Recommendation 2:

The Board recommends that the DOE set up a procedure to provide timely monitoring of the response and actions of the M&O contractor to the recommendations of the board of consultants.

Response:

A board of consultants from the underground tunneling industry has been utilized to provide independent review of the ESF construction and design activities. Its recommendations were considered by the Management & Operating Contractor (M&O); the M&O produced a close out report and provided it to DOE for comment in July 1996. The final report will be transmitted to DOE by August 30, 1996. The current focus of the board is on repository design activities required for the viability assessment. When input has been received from the board of consultants, the M&O contractor actions will be tracked.

Recommendation 3:

The Board supports initiation of a long-term, tunnel-scale thermal test as soon as possible and recommends that more thought be given to how more information can be obtained from all heater tests.

Response:

The DOE appreciates the Board's support of early initiation of drift-scale or tunnel-scale thermal testing in the ESF. Implementation of the *in situ* thermal testing program receives high priority, and construction of the thermal testing facility is proceeding on schedule. Ambient temperature measurements to characterize the single-heater test block have been made and installation of the instruments is under way. On August 26, 1996, the heater for this test was switched on as planned.

The May 1996 Program Plan, Revision 1, identifies that the initiation of the heat-up cycle of the drift-scale test

would occur in the July 1997 time frame. As a result of new planning assumptions, it is now expected that the drift-scale test heating phase will start toward the end of Fiscal Year 1997. The large block test at Fran Ridge, suspended at the end of Fiscal Year 1995, is planned to be resumed in Fiscal Year 1997. The heat-up cycle of the large block test will be started in February 1997. Small block tests and thermal property measurements in the laboratory will continue in Fiscal Year 1997.

The *in situ* thermal testing program has several components. The drift-scale test, by its large size, long duration, and complex suite of measurements, is intended to provide maximum information toward the understanding of heat-driven near-field processes. Plans and designs for the drift-scale test underwent in-depth Project review in recent months to ensure that Project needs have been addressed by the test. The plans and design of the test are summarized here and are followed by a description of the objectives.

- ! In the drift-scale test, a drift approximately 55 meters in length will be heated over a period of several years by electric heaters placed on the floor of the drift. The heaters will be similar in dimension to the waste package canisters to be used in the repository. In addition, a planar array of rod heaters, referred to as wing heaters, will be inserted into regularly spaced holes drilled in both walls of the drift at approximately the mid-height. The wing heaters are meant to simulate the presence of heated emplacement drifts on either side of an emplacement drift. They also enable a large volume of rock to be heated in a reasonable time.
- ! During the heating phase, the total heat output available from the canister heaters on the floor of the drift will be approximately 80kW, and that from the wing heaters will be approximately 200kW.
- ! After two years of continuous heating, test results will be evaluated to decide whether to continue the heating further and, if so, for how long. Heating may be continued for up to four years, to be followed by a period of controlled cooling and then natural cooling.
- ! The volume of rock surrounding the drift that will be heated above 100°C will exceed 30,000 cubic meters. The temperature in the drift wall will not be allowed to exceed 200°C to 250°C. The temperature in the floor immediately under the canister heaters will be higher. The rock close to the wing heaters may reach temperatures several hundred degrees higher.
- ! The heated drift will be similar in size and shape to repository emplacement drifts. It will be circular in cross section, 5 meters in diameter, and have a cast-in-place concrete invert. The first 35 meters of the drift will primarily be for observing thermo-hydrologic-chemical processes. Approximately 10 meters of this 35-meter length will be supported by steel sets and partial lagging. The rest will be supported by rockbolts and welded wire mesh. The next 10-meter length of the drift will be supported by a cast-in-place concrete liner, and the last 10 meters will be supported by precast concrete segments. The drift-scale test will help build a defensible understanding of the following: (a) large scale heat-transfer mechanisms including the role of convection, heat pipes, and enhanced diffusion; (b) moisture movement including the formation of dry-out and condensate zones, sub-boiling mobilization toward and away from the drift, shedding/drainage and downspout rewetting; (c) geochemical processes including return (to waste packages) water chemistry, evolution of near field water, changes in hydrologic pathways due to chemical processes, and changes in matrix transport properties; and, (d) thermomechanical processes including rock mass properties, changes in fracture aperture, new fracture formation and changes in near field stresses and displacements. More details about the objectives of the test and a brief description of the methods to achieve the objectives are given as follows:
- ! Prior to the installation of any instruments, the rock in the test area will be characterized. Such characterization will include mapping of all exposed surfaces; video logging all boreholes; measuring bulk permeability *in situ*; and measuring thermal expansion, thermal conductivity, deformation modulus, moisture saturation, porosity, density, moisture imbibition potential, and mineralogic-petrologic characteristics in the laboratory.

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- ! Various measuring systems will be installed in holes drilled from the heated drift (before heating) as well as from an observation drift parallel to the heated drift. Measurements will be made of rock temperature; movement of moisture in the rock; pressure, temperature and humidity of the air in the rock and in the drift; changes in rock-water chemistry; displacements in the rock; changes in the loads on ground support; and, changes in rock stress.
 - ! In the drift-scale test, rock temperature, which provides the most important signature toward understanding heat-driven processes, will be measured at more than 4000 locations in the volume of heated rock at a rate of at least one measurement per sensor per hour.
 - ! A number of different techniques will be employed to measure the moisture content of the rock as it changes with heating and cooling. The electrical resistivity tomography (ERT) method will measure the bulk moisture content of large volumes of rock. More than 1000 electrodes will be employed to make literally millions of individual resistivity measurements, and thus water contents, during the course of the drift-scale test. The well-established neutron-logging technique will be used to measure the moisture content of the rock in close proximity to 10 strategically located boreholes. If ground-penetrating radar proves effective in earlier trials, then it will also be used in the neutron logging holes to measure the moisture content of larger volume of rock. Continuous (one record per sensor per hour) measurements of pressure, temperature, and relative humidity of the air in approximately 100 chambers created using packers in 10 holes will also provide information for inferring the movement of moisture as the rock is heated and then cooled.
 - ! Air injection tests involving injection of air in one of the “packered” chambers and monitoring the response in the others will help in understanding how the bulk permeability of the rock changes with heating and cooling. Results of the air injection tests will also help in delineating the condensate zone, if any.
 - ! Up to 13 different chemical parameters will be monitored *in situ* at approximately 100 locations in 10 boreholes. Liquid water, if available at the sampling points, also will be collected periodically and will be analyzed from similar numbers of locations in these holes. This information, together with the mineralogic characteristics of the rock analyzed before heating and after cooling, will help in understanding the kinetics of rock-water interaction.
 - ! Coupons of potential waste package material will be placed in the rock and in the drift, and will be subjected to heating and cooling during the entire duration of the test. In addition, the heaters will be partly constructed from candidate waste package materials. Information on the response of these coupons and materials will enable the models of waste package material degradation to be refined.
 - ! The different ground-support systems in the heated drift are intended to provide information on how they perform under thermal stress, in an atmosphere of changing temperature and humidity, and at a drift scale, at least in size, if not time. Specifically, rock-support interaction; potential corrosion and degradation of support material; and possible debonding of concrete liners, shotcrete, and rockbolt grout will be studied in the drift-scale test. Also, approximately 100 measurements of displacements in the rock will be made periodically in approximately 15 holes. Literally thousands of rockbolt load and steel set strain measurements will be made during the course of the drift-scale test.
 - ! The drift-scale test will not provide information to directly address the issue of condensate zone coalescence. However, data from the drift-scale test, together with model simulations, will assist in investigating the likelihood of the phenomenon of condensate coalescence.

The drift-scale test is the most important component of the thermal tests, but the other tests also contribute to the understanding of thermal processes and are part of the Project’s thermal testing strategy.

The large block test provides timely information that will not be obtained in any of the other tests. The large block test has been designed specifically to create, if possible, and to observe a refluxing zone above the heaters. Formation of such a zone is not possible in the single heater test. Although refluxing is possible in the drift-scale test, the earlier results and controlled initial and boundary conditions are some of the reasons that make the large block test an important component of the thermal task. In addition, for both underground tests, rewetting after the thermal pulse decays is expected to be a slow process, with data from the *in situ* tests available only after many years. The large block geometry allows for much easier control of a forced rewetting phase, and it will provide results sooner for Viability Assessment and License Application. Furthermore, the large block test will have tracer tests to provide information on transport properties, which is not currently planned for either underground test. The only large-scale field tracer test to date has been for ambient temperature, saturated conditions at C-wells.

The single heater test also has value in that it finishes much sooner than the drift-scale test. It also fits in the Project strategy of progressing from simpler, smaller, shorter tests to more complex, bigger, longer tests. The simplified geometry of this test compared to the drift-scale test also has value in investigating thermal processes and in measuring the associated value of parameters such as thermal conductivity. One of the values of the test from a management viewpoint is that even though it is followed closely by the drift scale test, it provides valuable information on test construction, instrumentation, and coordination of the many groups involved in a complex test.

The large block test will provide the only *in situ* information of transport properties for unsaturated and/or thermally disturbed conditions. Also, there are tests conducted in the laboratory at above-ambient temperatures. The laboratory thermal tests are valuable in that they are the smallest scale, and thus the quickest and cheapest. Their scale also allows for better control of test conditions so that particular phenomena can be studied one at a time, instead of being combined as they are in larger tests. Although these small scale measurements are not representative of a drift-scale property, they can be correlated to the larger scale measurements made in the *in situ* tests. This correlation will then permit characterization of a large repository to proceed based largely on many smaller, easier tests, rather than relying solely on larger, more expensive tests.

RECOMMENDATIONS FOR HYDROGEOLOGY AND GEOCHEMISTRY

Recommendation 1:

The Board encourages the DOE to focus sufficient resources on verifying a sound conceptual model of flow in the unsaturated zone. This exploration and testing should provide the needed evidence for assigning quantitative bounds to the infiltration flux and percolation flux and should provide general support for the unsaturated zone flow model.

Response:

The DOE recognizes the need to test and refine the current conceptual model for the unsaturated zone hydrologic system at Yucca Mountain, as well as the need to establish quantitative bounds on the net-infiltration flux into the mountain and the percolation flux across the potential repository horizon. To accomplish these goals, the DOE is planning to continue and to augment current studies that are focused on these issues as follows:

- ! Systematic sampling within the ESF of fracture and lithophysal cavity in-filling materials for depositional-age determinations using uranium-series, carbon-14, and other techniques will be continued in order to construct a history of past water movement through the unsaturated zone.
- ! Systematic and feature-based sample collection within the ESF for chlorine-36 analyses will be continued.

These analyses, specifically the apparent occurrences of “bomb-pulse” chlorine-36 associated with mapped structural features in the ESF, may identify potential “fast” flow pathways through the unsaturated zone. Both the systematic and feature-based chlorine-36 sampling complement the fracture depositional age data and the interpretations derivable from the depositional ages.

- ! Detailed *in situ* hydrologic and pneumatic characterization of the Ghost Dance Fault will be conducted at two locations within the ESF to test the hypothesis that this feature may constitute a potential “fast” pathway for fluid flow in the unsaturated zone.
- ! Pneumatic, water-potential, and temperature monitoring will be continued in selected instrumented boreholes to determine ambient conditions within the unsaturated zone and to monitor dynamic changes in response to barometric fluctuations, to ESF-induced effects, and, possibly, to transient infiltration events. These data not only define conditions and processes within the unsaturated zone but they also provide data needed to calibrate the numerical predictive models of fluid flow in the unsaturated zone.
- ! An ESF-based field activity based on existing study plans is being designed specifically to test the prevailing unsaturated zone conceptual model and to obtain bounding estimates of the *in situ* percolation flux transiting the Paintbrush nonwelded hydrogeologic unit and moving downward across the potential repository horizon. This activity is intended to yield bounding estimates of water flux in the rock matrix and, possibly, in fractures under prevailing ambient conditions within the unsaturated zone at Yucca Mountain.
- ! As discussed under Risk and Performance Assessment Recommendation 3, an expert elicitation is to be conducted in 1997 to help the DOE evaluate the uncertainties in the unsaturated zone flow model.

Recommendation 2:

The DOE should place a stronger emphasis on predicting (or bounding) the release rates of important radionuclides from the EBS. Specifically, the DOE should evaluate alternative models for the seepage flux (water entering repository tunnels) and the concentration of neptunium in the water leaving the EBS.

Response:

The DOE agrees that predicting (or bounding) the release rate of important radionuclides from the engineered barrier system (EBS) is an important component that impacts the overall system performance. The DOE is evaluating a range of alternative conceptual models of seepage into the drifts. These models include using different scaling laws to correlate average “bulk” hydraulic properties to the likelihood and magnitude of seepage flux. Modeling of the effects of heterogeneity in rock properties and possible backfill properties on the possible distribution of seepage flux is also being conducted. The TSPA-1995 results illustrate the significance of the seepage flux into the drifts in controlling EBS release rates for the soluble radionuclides that may be transported in the aqueous phase. This significance has also been noted in the Waste Containment and Isolation Strategy. A number of sensitivity analyses are being undertaken in the current fiscal year to further evaluate the significance of the alternative seepage models.

The concentration of radionuclides leaving the EBS is dependent on a number of processes, including the dissolution rate of the spent fuel and the solubility of the key radionuclides in the water. Further analyses of spent fuel dissolution and neptunium solubility data (as well as numerical modeling of a range of possible solubility values) will allow alternative parameters to be used in TSPA analyses, the consequences of which will be evaluated in the current fiscal year. The validity of the range of parameters used will be the focus of ongoing analyses in Fiscal Year 1997.

RECOMMENDATIONS FOR ENGINEERED BARRIER SYSTEM

Recommendation 1:

The DOE should continue its efforts to identify engineering concepts that could help the EBS accomplish the three roles (complete containment, low mobilization, slow release) set out for it in the waste isolation strategy. Once identified, the DOE should set priorities for the concepts and decide which merit further investigation.

Response:

The DOE concurs with the Board's recommendation that it continue to identify approaches that will help the EBS accomplish its three goals and that it should determine those meriting further investigation and those that do not.

Planned work includes evaluation of the following approaches: the use of a long-lived container; the applicability of cladding credit for control of release; the addition of components such as backfill and drip shields; and the applicability of credit for the invert in controlling release from the EBS. These and other approaches need to be evaluated as part of an integrated design for the EBS. For example, backfill in the emplacement drifts might improve containment by keeping the waste packages dry, but it might also increase waste temperatures to the point that there is excessive mobilization of radionuclides in packages that breach early.

Recommendation 2:

The DOE should consider increasing the robustness of the EBS for preventing nuclear criticality after repository closure. In particular, the use of depleted uranium in filler, backfill, or invert material is a concept the program has yet to explore adequately.

Response:

Since the Board's report was written, two analyses have been completed: "Second Probabilistic Criticality Analysis: Generation and Evaluation of Internal Criticality Configurations" (1996) and "Probabilistic External Criticality Evaluation" (1996). The former deals with the consequences and, to a lesser degree, the probabilities of internal criticality events; the latter deals with probabilities of external criticality events. A third analysis, which discusses both probabilities and consequences of external criticality events, is in preparation. All three analyses indicate that both the probability and the consequences of criticality are small. In addition, recent studies that were not performed under the aegis of the Civilian Radioactive Waste Management Program have predicted that both the likelihood and the consequences of criticality events would be negligibly small. The DOE is continuing its program of criticality analysis, including the possibility of nuclear explosions, but does not expect to find any significant performance benefit in additional measures to decrease either the likelihood or consequences of criticality events. We will continue to view use of depleted uranium as one possible factor in criticality control. However, as the designs develop, the risk associated with criticality will continue to be a major determinant of their adequacy, and modifications will be considered that reduce risk without imposing disproportionate cost.

Recommendation 3:

Attempts should be made to locate data for iron artifacts to check extrapolations of corrosion models for waste packages based on short-term data.

Response:

The corrosion testing and modeling activity has been following the approach outlined in the ASTM procedure C-1174 (Prediction of Long-Term Behavior of Waste Package Materials Including Waste Forms Used in the Geologic Disposal of High-Level Nuclear Waste). This procedure provides a parallel path of testing and model development that includes both short- and long-term testing and the use of natural analogues.

The DOE has considered natural analogues and has reported its findings in a final report of the Natural Analogue Review Group entitled "Applications of Natural Analogue Studies to Yucca Mountain as a Potential High Level Radioactive Waste Repository," 1992. This document discussed what was known at the time regarding native iron and copper and metallic artifacts. The site of Santorini in Greece was specifically mentioned as an opportunity to study the fate of varied metallic artifacts buried in tuffaceous materials comparable to Yucca Mountain.

Since 1992, because of programmatic funding constraints, the budget for the natural analogue program has been limited, and little new work has been performed. A small effort was funded in Fiscal Year 1995 and partly into 1996 to examine the corrosion of candidate container materials in the geothermal wells in New Zealand; this work is currently on hold. However, the Project has followed the work of others, such as the NRC and other international programs. Funding has been identified to restart this effort in Fiscal Year 1997.

Recommendation 4:

The DOE should give a high priority to the corrosion research program for candidate waste package materials and should maintain an appropriate and consistent level of support for the next several years.

Response:

The DOE continues to recognize the importance of this effort in supporting waste package design and performance prediction. The need to confirm the performance of the candidate waste package materials, particularly those that contribute to containment, has been strongly addressed in the Waste Containment and Isolation Strategy. Long-term testing of these materials is underway at Lawrence Livermore National Laboratory following its "Activity Plan for Long-Term Corrosion Studies" (E-20-50, Rev. 2, 1995). The DOE also is performing short-term materials testing.

Recommendation 5:

The use of fillers to prevent void space collapse should be evaluated.

Response:

Since the Board's report was written, calculations have been completed on the loss of structural strength of the waste package as the containment barriers are degraded by corrosion. This work has been reported in several analyses and in a technical document. The waste package was found to have substantial mechanical integrity until the containment barriers have been severely thinned. Perforation seems likely to occur before extreme thinning. The DOE agrees that filler could provide a modest increase in mechanical support for a severely thinned container, but there are many disadvantages of filler. The cost and operational complexity of adding filler are significant, particularly for fuel that had been previously canistered. Recent results from thermal conductivity tests also suggest that even granular metallic fillers, such as steel shot, would raise internal temperatures substantially. Granular metallic fillers would be expected to

corrode and swell when the container perforates, and it is possible that such swelling would cause rupture of the container. Finally, filler would increase waste package mass. The DOE will continue to evaluate filler material as one option for enhancing criticality control or other elements of performance.

RECOMMENDATIONS FOR ENVIRONMENT AND PUBLIC HEALTH

Recommendation 1:

The DOE's socioeconomic program should expand the range of standard effects being considered to include those that will arise from increased transportation of materials, and personnel, possible social problems associated with "boom-and-bust" cycles, and the effects of controversial projects on the larger social system.

Response:

As the Board has observed, the socioeconomic program has studied and the DOE continues to evaluate potential impacts related to population change. In addition, the DOE examined the potential effects resulting from increased transportation of materials and personnel in the "Section 175 Report: Secretary of Energy's Report to the Congress Pursuant to Section 175 of the Nuclear Waste Policy Act, As Amended" (DOE/RW-0205, 1988). In an environmental impact statement for a proposed repository, that research will be addressed and an analysis will be made of issues regarding the full range of foreseeable potential impacts to human health and the environment, including socioeconomic impacts. The plans for the socioeconomic program currently do not include research of topics such as the effects of controversial projects on the larger social system, and it is unlikely that research into that issue will be pursued.

Recommendation 2:

An uncertain legal situation prevails with respect to special socioeconomic impacts. As a result, as long as the site-suitability guidelines remain in effect, the Board believes a modest research and analytic effort would be prudent. The DOE should concentrate its efforts on deriving worst-case, bounded estimates of what consequences might arise and how long those impacts might last.

Response:

The Department does not have an obligation under the site suitability guidelines to evaluate "special" socioeconomic impacts, i.e. those from perceived risk. The Department has, however, attempted to remain cognizant of the research and academic debate that have transpired in this relatively new field of inquiry, and has sponsored work by university and national laboratory professionals on this topic. While some limited, additional work may be feasible in this area, DOE must ensure any additional expenditure of resources on special socioeconomic impacts is consistent with Congressional redirection of the Program.

Appendix E

Nuclear Waste Technical Review Board

Publications

The following publications are available from the Nuclear Waste Technical Review Board.

First Report to the U.S. Congress and the U.S. Secretary of Energy. March 1990.

The first report outlines the legislative history of the nation's spent fuel and high-level waste management program. The Board's evolution is described, along with its protocol, panel structure, and reporting requirements. The report identifies major issues and highlights five cross-cutting issues.

Second Report to the U.S. Congress and the U.S. Secretary of Energy. November 1990.

The Board's second report makes 20 recommendations concerning tectonic features and processes, geoengineering considerations, the engineered barrier system, transportation and systems, environmental and public health issues, and risk and performance analysis.

Third Report to the U.S. Congress and the U.S. Secretary of Energy. May 1991.

The third report offers 15 recommendations on the exploratory shaft facility, repository design, risk-benefit analysis, waste package plans and funding, spent fuel corrosion performance, transportation and systems, environmental program concerns, risk and performance assessment, quality assurance, and radionuclide sorption data. Background information on the German and Swedish nuclear waste disposal programs is included.

Fourth Report to the U.S. Congress and the U.S. Secretary of Energy. December 1991.

The fourth report makes ten recommendations on: exploratory studies facility (ESF) construction; test prioritization; rock mechanics; tectonic features and processes; volcanism; hydrogeology and geochemistry in the unsatu-

rated zone; the engineered barrier system; repository regulations; the DOE performance assessment program; and quality assurance in the Yucca Mountain project. The report offers insights from the Board's visit with officials from the Canadian nuclear power and spent fuel disposal programs.

Fifth Report to the U.S. Congress and the U.S. Secretary of Energy. June 1992.

The Board's fifth report focuses on the cross-cutting issue of thermal loading. It explores thermal-loading strategies (U.S. and others) and details the Board's position on the implications of thermal loading for the U.S. radioactive waste management system. The report offers 15 recommendations to the DOE on the following subjects: ESF and repository design enhancements, repository sealing, seismic vulnerabilities (vibratory ground motion and fault displacement), the DOE approach to the engineered barrier system, and transportation and systems program status.

Sixth Report to the U.S. Congress and the U.S. Secretary of Energy. December 1992.

The sixth report offers seven recommendations on the dangers of a schedule-driven program; the need for top-level systems studies; the impact of defense high-level waste; the use of high capacity, self-shielded waste package designs; and the need for prioritization among the numerous studies included in the site-characterization plans. The Board also offers insights into the high-level waste management programs in five countries and discusses areas that might be applicable to the U.S. program. Background information on the Finnish and Swiss programs is presented.

Special Report to Congress and the Secretary of Energy. March 1993.

The Board's seventh report highlights three policy issues:

the program is driven by unrealistic deadlines, there is no integrated waste management plan, and program management needs improvement.

Underground Exploration and Testing at Yucca Mountain A Report to Congress and the Secretary of Energy. October 1993.

This report (eighth in the NWTRB series) focuses on the exploratory studies facility at Yucca Mountain. The Board makes three general recommendations. First, the DOE should develop a comprehensive strategy that integrates exploration and testing priorities with the design and excavation approach for the exploratory facility. Second, underground thermal testing should be resumed as soon as possible. Third, the DOE should establish a geoenvironmental board with expertise in the engineering, construction, and management of large underground projects.

Letter Report to Congress and the Secretary of Energy. February 1994.

This report restates a recommendation for an independent review of the Office of Civilian Radioactive Waste Management's management and organizational structure. It adds two additional recommendations: ensure sufficient and reliable funding, and expand current efforts to integrate the views of the various stakeholders.

Report to The U.S. Congress and The Secretary of Energy — January to December 1993. May 1994.

This report reviews the nuclear waste disposal programs of Belgium, France, and the United Kingdom; the radiation protection standards being reviewed by the National Academy of Sciences; and, using "future climates" as an example, the DOE's approach to resolving difficult issues. Recommendations include the use of a systems approach, prioritization of site-suitability activities, use of total system performance assessment and expert judgment, and the dynamics of the Yucca Mountain ecosystem.

Report to the U.S. Congress and the Secretary of Energy: 1994 Findings and Recommendations. March 1995.

This report covers the DOE's Program Approach, the emerging waste isolation strategy, the transportation program, minimum exploratory requirements, and thermal-loading issues. The Board reviews volcanism as an example of a difficult issue needing resolution. The Board also

comments on the Japanese nuclear waste disposal program. Sixteen recommendations are offered on a wide range of subjects.

Disposal and Storage of Spent Nuclear Fuel – Finding the Right Balance. March 1996.

This report reviews interim storage of commercial spent nuclear fuel and the need to develop a federal centralized storage facility. The Board concludes that efforts should remain focused on permanent geologic disposal. Planning for a federal centralized spent fuel storage facility and the required transportation infrastructure begin now, but actual construction should be delayed until after a site-suitability decision is made about the Yucca Mountain site.

Report to the U.S. Congress and the Secretary of Energy: 1995 Findings and Recommendations. April 1996.

This report provides an overview of the Department of Energy high-level waste management program, reports on Board Panel activities, and reviews Board activities during 1995. Eighteen recommendations are offered on a wide range of subjects.

Nuclear Waste Management in the United States – The Board's Perspective. June 1996.

This publication was developed from remarks made by Dr. John Cantlon, Chairman of the Nuclear Waste Technical Review Board, at Topseal '96, an international conference on nuclear waste management and disposal. The publication highlights the Board's views on the status of the U.S. program for management and disposal of commercial spent nuclear fuel and provides a brief overview of the program's organization.

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Glossary

The following list of terms was compiled to aid in reading the Board's reports. It is not meant to be a formal glossary, nor to have the completeness of a dictionary, but to help the reader understand some of the terms used in this report.

Accessible environment:

The earth's surface and the rock more than five kilometers beyond the repository.

Advanced conceptual design:

Conceptual design is the first phase of design in which all alternative configurations and concepts are defined and evaluated. The final product of the advanced conceptual design phase is a definitive design, one in which all of the options have been evaluated and a single configuration decided upon.

Analogue:

A phenomenon that can provide information on or add understanding to aspects of repository performance. Analogues are of two types: natural and anthropogenic. Natural analogues occur through natural phenomena. Anthropogenic analogues result from human activity. An "archaeological analogue" is an anthropogenic analogue resulting from the activities of ancient cultures.

Areal mass loading:

The concentration of emplaced spent fuel, averaged over the area of the repository. This is expressed in mass of heavy metal per unit area, e.g. kilograms per square meter or in metric tons per acre.

Assembly:

A group of linked rods or tubes that contain nuclear fuel.

Backfill:

Solid material placed into excavated areas underground to fill voids.

Biosphere:

The portion of the earth that supports self-sustaining and self-regulating ecological systems.

Bomb Pulse:

See **Chlorine-36**

Borehole:

A hole bored or drilled into the earth to obtain geologic samples, to allow injection or extraction of materials, or for other purposes.

Borosilicate glass:

Glass containing boron and silica and used to immobilize or encapsulate and stabilize commercial or defense reprocessed high-level waste.

Calcite:

One of the commonest minerals (CaCO_3), the principal constituent of limestone. Calcite deposited in fractures and voids in Yucca Mountain provides information about past movement of water through the mountain.

Cask:

A container used to store and, perhaps, transport irradiated nuclear fuel or high-level nuclear waste. It provides both physical and radiological protection and dissipates heat.

Cathodic protection:

Protection of a metal from corrosion in the presence of an electrolyte (such as water containing dissolved salts) by providing physical contact with a more electropositive metal that will corrode first.

Characterization:

Collecting information necessary to evaluate the suitability of a region or site for geologic disposal. Data from characterization also will be used during licensing.

Chlorine-36 (^{36}Cl):

A long-lived radioactive isotope of chlorine produced by irradiation of natural chlorine, argon or other materials by cosmic rays or neutrons. Atmospheric testing of nuclear weapons in the 1950's temporarily increased concentrations of chlorine-36. The resulting "bomb pulse" levels of chlorine-36 can sometimes serve as a tracer to determine how precipitation from the 1950's has moved through soil and rocks such as those present at Yucca Mountain.

Container:

A receptacle used to hold radioactive material.

Corrosion-resistant materials:

Materials that fail primarily by localized corrosion, and that tend to fail more slowly than corrosion-allowance materials.

Critical:

Able to sustain a nuclear chain reaction.

Defense high-level waste:

High-level waste generated by defense programs, as distinguished from waste generated by commercial and research facilities.

Diffusion:

A process in which molecules or atoms spread out in space due to their random thermal motion.

Dispersion:

The spreading of a plume of radionuclides due to the inhomogeneities of the flow field.

Disposal:

The isolation of radioactive materials from the accessible environment with no intent of recovering them.

Drift:

A near-horizontal, excavated passageway through the earth; a tunnel.

Dry transfer:

Moving spent nuclear fuel between containers in air rather than under water.

Engineered barrier system:

The constructed components of a disposal system designed to retard or prevent the release of radionuclides from the underground facility. They can include the waste forms, fillers, waste containers, shielding, material placed over and around such containers, and backfill materials.

Environmental impact statement (EIS):

A detailed written statement to support a decision whether to proceed with major actions affecting the quality of the human environment.

Evapotranspiration:

Transfer of water from soil or rocks to the atmosphere by

evaporation or transpiration of plants.

Expert judgment:

The judgment of a person with a high degree of skill in or knowledge of a subject.

Exploratory studies facility (ESF):

An underground facility constructed for the purpose of performing exploration and testing of the site's suitability to host a geologic repository.

Fast Pathways:

Underground fractures or features that allow fluids to flow more quickly than the surrounding media.

Fault:

A plane in the earth along which differential slippage of the rocks on either side has occurred.

Fault displacement:

The result of relative movement of the rocks on opposite sides of a fault, such as occurs during an earthquake.

Filler:

Material used to occupy empty spaces in a waste package.

Fission:

Splitting of a uranium or transuranic atom into two or more parts, called fission products. Fission releases thermal energy which can be converted to electrical energy at a nuclear power plant.

Fission product:

A nuclide produced by the fission of a heavier element. Many fission products are radioactive and some have very long half-lives.

Flux:

The rate at which ground water flows through the earth. Flux is the volume of flow per unit area of earth perpendicular to the direction of flow.

Fracture:

Any break in a rock (i.e., a crack, joint, or fault), whether or not accompanied by displacement.

Fracture flow:

Flow through the fractures in rock.

Fuel rod:

A tube, typically made of zircaloy, into which fuel, usually in the form of uranium oxide pellets, is sealed. Many linked fuel rods form an assembly or bundle that is used as fuel in a nuclear power plant.

Geochemistry:

The study of the chemical and physical properties of the minerals, rocks, and waters at the repository site that might affect the migration of radionuclides.

Geologic block:

An undeformed mountain-sized section of rock that may be bounded by large faults and/or large-scale topographic features (e.g., river valleys). The term is also used to refer to the repository block.

Geologic repository:

A facility for the disposal of radioactive waste in excavated geologic media, including surface and subsurface areas of operation and the adjacent portion of the natural setting.

Ground water:

Water that exists or flows beneath the land surface.

Ground-water travel time:

The time it takes ground water to travel from the edge of the disturbed zone to the accessible environment.

High-level waste:

Highly radioactive material from reprocessing spent nuclear fuel, including liquid waste produced directly in reprocessing or any solid material derived from such liquid waste. Any other highly radioactive material that the Nuclear Regulatory Commission determines requires permanent isolation by disposal in a geologic repository.

Host rock:

The rock in which radioactive waste will be emplaced; specifically, the geologic materials that will surround or be in close proximity to a repository.

Hydrology (hydrogeology):

The science dealing with surface and ground water. At the Yucca Mountain site, emphasis is placed on the study of liquid transport through the rock matrix and fractures. Ground water is a primary means by which radionuclides could be transported from the repository to the accessible environment.

Infiltration:

Water entering soil or rocks after precipitation events rather than running off into rivers, streams, ponds, etc. The terms “infiltration” and “net infiltration” are also used to refer to water that penetrates deeply into soil or rocks (beneath plant root zones) rather than returning to the atmosphere by evapotranspiration.

Interim storage:

Storage of spent fuel or high-level waste with the intention and expectation that the waste will later be removed to a permanent disposal site.

Interim storage facility:

A facility for storing spent nuclear fuel and high-level nuclear waste prior to permanent disposal in a repository.

Invert:

The part of the bottom of a tunnel that has been made level by the addition of materials.

Isolation:

See **waste isolation**

Isotope:

Atomic species of a given element having different atomic weights but the same atomic number.

Leach:

To partially or completely dissolve and remove chemical components of a solid, usually by water. The rate at which this occurs is the leach rate.

License application:

A document submitted to the Nuclear Regulatory Commission containing general information and a safety analysis for a nuclear reactor, geologic repository, or an interim storage facility for spent nuclear fuel and high-level radioactive waste.

Low-level (radioactive) waste:

Radioactive material that is neither high-level radioactive waste, spent nuclear fuel, transuranic waste, nor uranium or thorium mill tailings.

Matrix:

In hydrology, the solid framework of a porous system.

Metric ton:

1,000 kilograms (about 2,205 pounds).

Metric ton of uranium (MTU):

A measure of the quantity of spent fuel. About 2,000 MTU is generated by power plants in the U.S. annually and their total projected inventory is anticipated to be 85,000 MTU.

Monitored retrievable storage (MRS) facility:

An interim storage facility.

Multipurpose canister (MPC):

A sealed, metallic container holding spent nuclear fuel assemblies in a dry, inert environment and inserted into different outer containers for storage, transportation, and disposal.

Natural analogue:

(See **analogue**.)

Nevada Test Site (NTS):

An area of southern Nevada, owned and operated by the U.S. Department of Energy, devoted primarily to the underground testing of nuclear weapons.

Nonwelded tuff:

A tuff that has not been hardened and welded together by intense temperature and pressure and contains relatively fewer fractures than welded tuff.

Nuclear Waste Fund:

A separate fund within the U.S. Treasury established by the Nuclear Waste Policy Act (NWPA) to assure that the costs of commercial spent fuel management and disposal are borne by the generators of the waste. Civilian utility payments for spent fuel disposal are deposited in the fund to be used by Congress for purposes defined in the NWPA. Payments in excess of current appropriations are invested in treasury securities that pay interest to the fund.

Order of magnitude:

An estimate of size or magnitude expressed as a power of ten (i.e. 10^2 , 10^3).

Peer review:

A critical review performed by those who have technical expertise equivalent to but are independent from those who performed the original work.

Percolation:

As used by the Yucca Mountain Project, water moving through the location where a repository would be built at Yucca Mountain. At specific points within the proposed

repository location, percolation may differ from (net) infiltration if fractures, bedding planes or other geologic structures enhance, impede, or divert the flow of water as it moves downward through the mountain.

Performance assessment (PA):

An analysis that predicts the behavior of an entire system or a part of a system under a given set of conditions.

Performance confirmation:

Tests, experiments, and analyses conducted to verify predictions of repository performance after waste emplacement.

Portal:

The entrance to a tunnel.

Pneumatic:

Of or pertaining to air, especially the movement of air through Yucca Mountain.

Preclosure:

The time before the repository is closed.

Quality assurance (QA):

The planned and systematic actions necessary to provide adequate confidence that a structure, system, or component is developed or constructed according to plans and specifications and will perform satisfactorily.

Radioactivity:

The spontaneous emission of radiation from the nucleus of an atom. Radioisotopes of elements lose particles and energy through the process of radioactive decay. Radioactivity is measured in terms of the number of nuclear disintegrations occurring in a unit of time. Units of radioactivity are the curie (Ci) and the becquerel (Bq).

Radionuclide:

A radioactive isotope, as specified by its atomic number, atomic mass, and energy state.

Radionuclide transport:

The movement of radionuclides, generally in liquid or gas forms, through a rock formation.

Recharge:

Either the process of adding water to the saturated zone or the water added.

Repository:

See **geologic repository**

Repository block:

The portion of Yucca Mountain in which a proposed repository may be built. See **geologic block**

Retrievability:

The ability to remove waste packages from the repository.

Risk:

The possibility of suffering harm or loss due to some event. The magnitude of the risk depends on both the probability of occurrence of an event and the consequences should the event occur.

Saturated zone:

The part of the earth's crust in which all empty spaces are filled with water.

Seismicity (seismic activity):

The worldwide, regional, or local distribution of earthquakes over a period of time.

Silica:

Natural silicon dioxide.

Site characterization:

See **characterization**.

Site recommendation:

The final step before licensing is the Secretary of Energy's recommendation to the President whether to develop a repository at Yucca Mountain.

Site suitability:

A high probability that a site, along with engineered barriers, can provide long-term waste isolation.

Siting guidelines:

The guidelines of 10 CFR 960 which are to be used by the DOE in assessing the suitability of the site.

Sorption:

Retarding transport of radionuclides by adhesion to the geologic materials that they flow through.

Spent fuel storage:

See **interim storage**.

Spent nuclear fuel:

Fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing.

Thermal load:

The amount of heat produced by emplaced waste, and affecting the near field and overall repository material, including geophysical and engineered barriers (usually measured in kilowatts per acre).

Thermal-loading strategies:

Placing waste in a repository so that the heat produced by it will cause specific effects on repository performance. These strategies are based on whether it is desirable for the repository to be at a temperature below or above the boiling point of water, and the effect different temperature ranges will have on long-lived waste packages.

Total system life cycle cost (TSLCC):

An estimate of the total cost of the spent fuel management system including site characterization, repository operations, spent fuel transportation and repository closure.

Total system performance assessment (TSPA):

Analyses undertaken by the Department of Energy to assess the ability of the potential repository at Yucca Mountain to provide long-term waste isolation.

Transparent:

Easy to detect or perceive. Using clear language and easily understood concepts and/or assumptions to arrive at, credible, traceable, and logical conclusions.

Tuff:

Rock composed of compacted volcanic ash. Tuff is usually porous and often relatively soft.

Tunnel boring machine (TBM):

A machine that mechanically excavates tunnels in rock by use of a rotating cutterhead the diameter of the tunnel to be excavated.

Underground facility:

The underground part of a geologic repository where spent fuel and high-level wastes are emplaced, but excluding shafts, ramps, boreholes and their seals.

Unsaturated rock:

A rock in which some or all of the connected interstices or voids are filled with air.

Unsaturated zone:

Rock/geologic formation that is located above the regional ground-water table.

Uranium:

A naturally radioactive element with the atomic number 92 and an atomic weight of approximately 238. The two principal naturally occurring isotopes are the fissionable U-235 (0.7% of natural uranium) and U-238 (99.3% of natural uranium). Uranium may be measured in metric tons of uranium (MTU).

Utilities:

Commercial entities that provide electricity to users for a fee. Utility companies that generate power using nuclear reactors collect money from their customers that goes into the Nuclear Waste Fund.

Viability assessment (VA):

An estimate of the likelihood of success for geologic disposal at the Yucca Mountain site, based on repository and waste package designs, a total system performance assessment, a license application plan, and repository cost and schedule estimates.

Waste canister:

A container holding waste.

Waste form:

Radioactive waste materials and any encapsulating or stabilizing matrix. Examples include used reactor fuel elements and borosilicate glass "logs."

Waste isolation:

Separation of waste from the environment so that any radioactive material reentering the environment will be kept within prescribed limits.

Waste isolation strategy:

The Department of Energy's specification of the barriers and natural phenomena it will rely on to isolate waste at the Yucca Mountain repository.

Waste package:

The waste form, plus fillers, containers, shielding, packing, or other absorbent materials immediately surrounding an individual waste container.

Water table:

An underground boundary below which the rock interstices are filled with water and above which the interstices are not filled with water.

Welded tuff:

Rock made of volcanic ash that has been hardened and welded together by heat, pressure, and possibly the introduction of cementing minerals. It contains more fractures than nonwelded tuff.

Zeolites (zeolitic materials):

A large group of white, faintly colored or colorless materials characterized by their easy and reversible loss of water of hydration and their high adsorption capacity for metal ions dissolved in water.